U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Method to Identify Wells that Yield Water that will be Replaced by Water from the Colorado River Downstream from Laguna Dam in Arizona and California

Water-Resources Investigations Report 00–4085

Prepared in cooperation with the
BUREAU OF RECLAMATION

USGS
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By SANDRA L. OWEN-JOYCE, RICHARD P. WILSON, MICHAEL C. CARPENTER, *and* JAMES B. FINK

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Tucson, Arizona
2000

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
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CONTENTS

PLATES

[Plates are in pocket]

FIGURES

FIGURES—Continued

TABLES

CONVERSION FACTORS

Multiply	By	To obtain
inch	2.54	centimeter
foot	0.3048	meter
mile	1.609	kilometer
square mile	2.590	square kilometer
acre	0.4047	square hectometer
acre-foot	0.001233	cubic hectometer
cubic foot per second	0.02832	cubic meter per second
gallon per minute	0.06309	liter per second

DEFINITION OF TERMS

Selected hydrologic and geologic terms used in the report are defined below. Terms were adapted from Bates and Jackson (1987), Lohman and others (1972), Meinzer (1923), U.S. Water-Resources Council (1980), and Wilson and Owen-Joyce (1994).

Accounting surface—The accounting surface represents the elevation and slope of the unconfined static water table in the river aquifer outside the flood plain of the Colorado River that would exist if the river were the only source of water to the river aquifer. The accounting surface was generated by using profiles of the Colorado River.

Acre-foot—The volume of water required to cover 1 acre to a depth of 1 foot; 43,560 cubic feet or 325,851 gallons.

Aquifer—A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Bedrock—Consolidated rocks that form the bottom and sides of the basins that underlie the Colorado River valley and adjacent tributary valleys and the mountain masses that rim the basins and valleys. The bedrock is nearly impermeable and is a barrier to ground-water flow.

Flood plain—A surface or strip of relatively smooth land adjacent to a river channel, constructed by the present river in its existing regimen and covered with water when the river overflows its banks. In this report, the flood plain is that part of the Colorado River valley that has been covered by floods of the modern Colorado River as it meandered prior to the construction of Hoover Dam and includes the flood plain of the Gila River from the Laguna and Gila Mountains to the confluence with the Colorado River. The flood plain commonly is bounded by terraces and alluvial slopes that rise to the foot of mountains that rim the valley. The flood plain ranges in width from about 1 mile at Laguna Dam to about 10 miles where the Colorado and Gila flood plains join.

Geologic formation—A persistent body of igneous, sedimentary, or metamorphic rock, having easily recognizable boundaries that can be traced in the field without recourse to detailed paleontologic or petrologic analysis, and large enough to be represented on a map as a practical or convenient unit for mapping and description. Formations are described in geologic literature and have formal names (Bouse Formation) or informal names (younger alluvium).

Limotrophe section—The reach of the Colorado River that forms the international boundary between the United States and Mexico.

Milligal—A unit of measure of gravitational acceleration. One milligal equals 0.001 Gal, which equals 0.00001 meter per second squared. Gravitational acceleration at the earth’s surface is approximately 980 Gals.

River aquifer—The aquifer that consists of permeable sediments and sedimentary rocks that are hydraulically connected to the Colorado River so that water can move between the river and the aquifer in response to withdrawal of water from the aquifer or differences in water-level elevations between the river and the aquifer.

Sea level—In this report "sea level" refers to the National Geodetic Vertical Datum of 1929—A geodetic datum derived from a general adjustment of the first order level net of the United States and Canada, formerly called “Sea Level Datum of 1929.”

Section, Township (T.), and Range (R.)—Locations used by the U.S. Geological Survey are in accordance with the Bureau of Land Management’s system of land subdivision. The surveys of lands encompassed by the study area are referenced to the Gila and Salt River (G&SR) meridian and base line or the San Bernardino (SB) meridian and base line.

Sediment—Solid fragmental material that originates from weathering of rocks and is transported or deposited by air, water, or ice, or that accumulates by natural means, such as chemical precipitation or secretion by organisms, and that forms in layers on the Earth's surface in unconsolidated form. Sediments generally consist of alluvium, mud, clay, silt, sand, gravel, boulders, carbonate muds, shell fragments, and organic material; in basins of interior drainage, sediments include salt (halite), gypsum, and other evaporite minerals.

Sedimentary rocks—Rocks resulting from consolidation of sediments. The rocks can be formed in marine, estuarine, and continental environments.

Static head—The height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point. The static head is the sum of the elevation head and the pressure head.

Static water level—The level of water in a well that is not being affected by ground-water withdrawal. The level to which water will rise in a tightly cased well under its full pressure head.

Water table—The surface in an unconfined aquifer at which pressure is atmospheric and below which the permeable material is saturated with water. The water table is the level at which water stands in wells that penetrate the uppermost part of an unconfined aquifer.

Method to Identify Wells That Yield Water That Will Be Replaced by Water from the Colorado River Downstream from Laguna Dam in Arizona and California

By Sandra J. Owen-Joyce, Richard P. Wilson, Michael C. Carpenter, *and* James B. Fink[1]

Abstract

Accounting for the use of Colorado River water is required by the U.S. Supreme Court decree, 1964, *Arizona v. California*. Water pumped from wells on the flood plain and from certain wells on alluvial slopes outside the flood plain is presumed to be river water and is accounted for as Colorado River water. The accounting-surface method developed for the area upstream from Laguna Dam was modified for use downstream from Laguna Dam to identify wells outside the flood plain of the lower Colorado River that yield water that will be replaced by water from the river. Use of the same method provides a uniform criterion of identification for all users pumping water from wells by determining if the static water-level elevation in the well is above or below the elevation of the accounting surface. Wells that have a static water-level elevation equal to or below the accounting surface are presumed to yield water that will be replaced by water from the Colorado River. Wells that have a static water-level elevation above the accounting surface are presumed to yield river water stored above river level.

The method is based on the concept of a river aquifer and an accounting surface within the river aquifer. The river aquifer consists of permeable sediments and sedimentary rocks that are hydraulically connected to the Colorado River so that water can move between the river and the aquifer in response to withdrawal of water from the aquifer or differences in water-level elevations between the river and the aquifer. The subsurface limit of the river aquifer is the nearly impermeable bedrock of the bottom and sides of the basins that underlie the Yuma area and adjacent valleys. The accounting surface represents the elevation and slope of the unconfined static water table in the river aquifer outside the flood plain of the Colorado River that would exist if the river were the only source of water to the river aquifer. The accounting surface was generated by using water-surface profiles of the Colorado River from Laguna Dam to about the downstream limit of perennial flow at Morelos Dam. The accounting surface extends outward from the edges of the flood plain to the subsurface boundary of the river aquifer. Maps at a scale of 1:100,000 show the extent of the river aquifer and elevation of the accounting surface downstream from Laguna Dam in Arizona and California.

INTRODUCTION

Flow in the Colorado River is regulated by a series of dams, and releases of water through these regulatory structures are controlled by the United States. Water stored in reservoirs is released to meet downstream water requirements, to make storage available for flood control, and to generate power. Water from the Colorado River is diverted or pumped and used to irrigate croplands; to meet municipal, domestic, and industrial uses; and to support wildlife habitat in the marshes along the

[1] Hydrogeophysics, Inc., Tucson, Arizona

river. Water also is pumped from wells in the Colorado River drainage area and adjacent valleys for agricultural, municipal, industrial, and domestic uses. In the United States, accounting for the use of Colorado River water is required by a decree (U.S. Supreme Court, 1964); a report that contains records of diversions, returns, and consumptive use of water by individual water users is published annually (Bureau of Reclamation, 1965–99).

Water pumped from wells on the flood plain and from certain wells on alluvial slopes outside the flood plain is presumed to be Colorado River water and is accounted for as Colorado River water. Water pumped from some wells outside the flood plain has not been included in the accounting because the subsurface limits of the aquifer that is hydraulically connected to the river were not defined. Before 1994, no method was available for identifying wells that are presumed to yield water that will be replaced by water from the river and wells that are presumed to yield water that will be replaced by water from precipitation and inflow from adjacent tributary valleys. To aid in implementing the Supreme Court decree, the U.S. Geological Survey developed a tool, which is referred to as the "accounting-surface method," for use by the Bureau of Reclamation to identify wells outside the flood plain of the lower Colorado River between the east end of Lake Mead and Laguna Dam that are presumed to yield water that will be replaced by water from the river (Wilson and Owen-Joyce, 1994). The accounting-surface method is based on the concept of a river aquifer and an accounting surface within the river aquifer (see section entitled "Definition of Terms").

The same river aquifer exists upstream and downstream from Laguna Dam. To provide a uniform criterion of identification that is based on hydrologic principles for all users pumping water from wells presumed to yield water that will be replaced by water from the Colorado River, the U.S. Geological Survey, in cooperation with the Bureau of Reclamation, applied the accounting-surface method to the area downstream from Laguna Dam. The area in the United States downstream from Laguna Dam extends to the Gila River near Dome streamflow-gaging station to cover the same area included in the Lower Colorado River Accounting System (Owen-Joyce and Raymond, 1996; Bureau of Reclamation, 1997–99) and is collectively referred to as "the Yuma area." The Yuma area is bounded on the east by the Laguna, Gila, and Tinajas Altas Mountains; on the north by the Chocolate and Cargo Muchacho Mountains; and on the west by Pilot Knob (fig. 1). Application of the accounting-surface method for use in the Yuma area required the delineation of the physical river aquifer that is hydraulically connected to the Colorado River and generation of an accounting surface. A sparsity of data in southeast Imperial County off the flood plain of the Colorado River and in the Gila River canyon required that the study be expanded to include the drilling of 11 wells. Because the study was regional in scope, detailed site-specific investigations that would be required to precisely define the extent, thickness, or hydraulic properties of the river aquifer were not included.

The main difference between the areas upstream and downstream from Laguna Dam is the amount of tributary water available for recharge to the river aquifer. Upstream from Laguna Dam, the sources of recharge to the river aquifer are the Colorado River, precipitation, and inflow from tributary valleys. The accounting-surface method is used to identify wells that are presumed to yield water that will be replaced by water from the river and those that are presumed to yield water that will be replaced by water from precipitation and inflow from tributary valleys. Characteristics of the river aquifer upstream from Laguna Dam are:

- The river aquifer is a closed system—the aquifer is surrounded by bedrock, which is a barrier to ground-water flow except at the downstream end where a small quantity of ground water flows beneath Laguna Dam.
- The main control of water-table elevation and slope in the river aquifer is recharge from and discharge to the main channel and reservoirs of the Colorado River. The channel and reservoirs convey most of the surface water through the system. Locally, drainage ditches affect the water-table elevation and slope on the flood plain.
- Recharge to the river aquifer is available from the Colorado River, precipitation, and inflow from adjacent tributary valleys.
- Wells yield water that eventually will be replaced by water from the river or from adjacent tributary valleys.

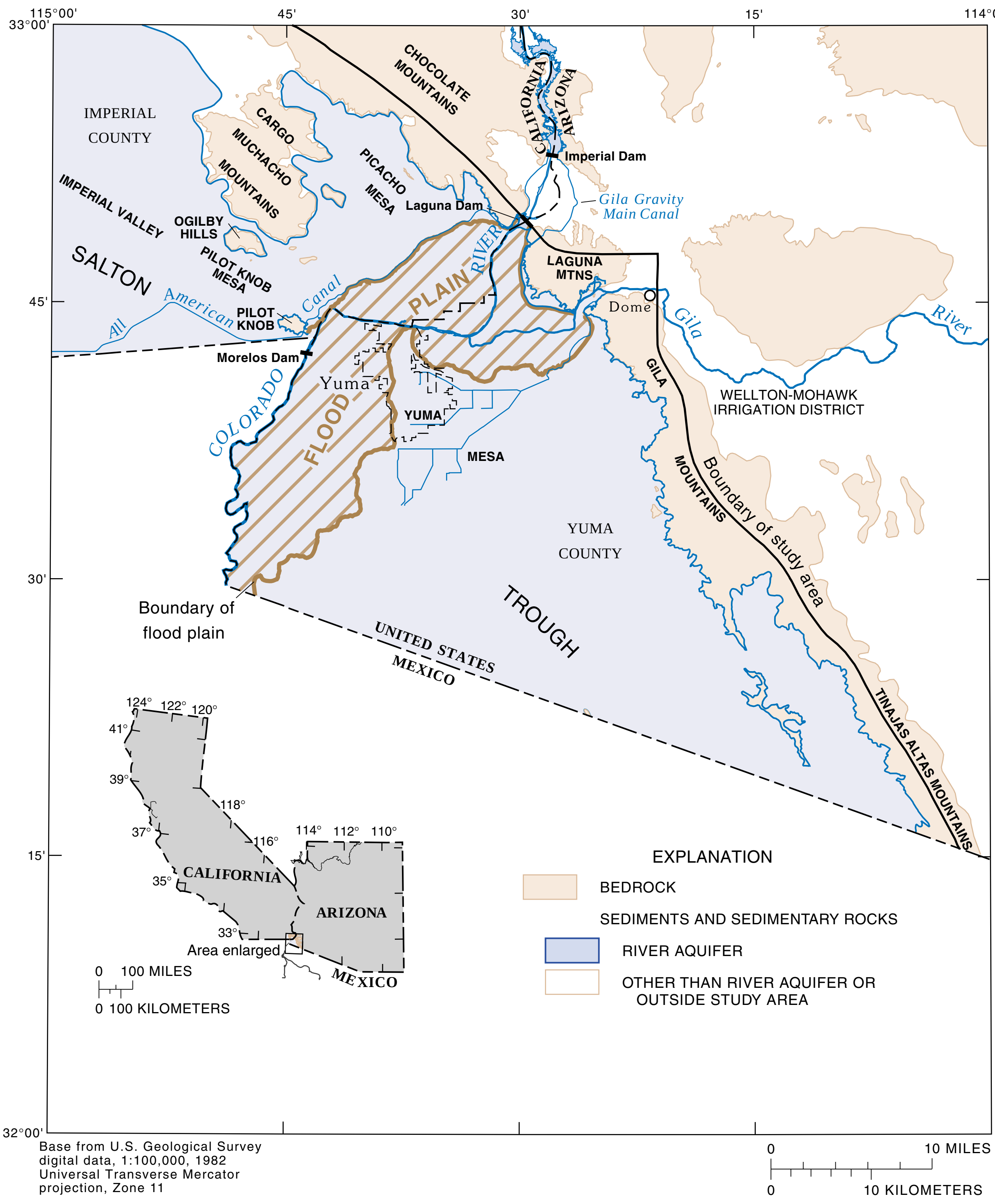


Figure 1. The lower Colorado River and the areal extent of the river aquifer downstream from Laguna Dam, Arizona and California.

Downstream from Laguna Dam, the Colorado River is the source for nearly all recharge to the river aquifer. The complex surface-water and ground-water system that exists in the area downstream from Laguna Dam is the result of more than 100 years of water-resources development. The construction and operation of canals provides the means to divert and distribute Colorado River water to irrigate agricultural lands on the flood plains and mesas along the Colorado and Gila Rivers, in Imperial and Coachella Valleys, and in the area upstream from Dome along the Gila River. Water is withdrawn from wells for irrigation, dewatering, and domestic use. The area downstream from Laguna Dam borders additional areas of agricultural development in Mexico where Colorado River water also is diverted for irrigation. Characteristics of the river aquifer downstream from Laguna Dam are:

- The river aquifer is an open system—the aquifer extends to bedrock, which is a barrier to ground-water flow except where the aquifer is continuous in the subsurface at the upstream end beneath Laguna Dam, along the boundary with Mexico, through the Gila River canyon, and into Imperial Valley north of Pilot Knob.
- Ground water moves in the river aquifer beneath the international boundary with Mexico in response to recharge from canals, irrigated fields, and the Colorado River and withdrawal from wells used for irrigation, recovery, municipal and domestic supply, or drainage.
- The main controls of water-table elevation and slope in the river aquifer are recharge from Colorado River water diverted into unlined canals and applied to croplands and discharge to wells, drainage ditches, and the channel of the river when flow is regulated to meet downstream requirements. Nearly all flow in the channel of the Colorado River is diverted into canals upstream from Laguna Dam, and the river is a drain except during flood-control releases when the river becomes a source of recharge to the river aquifer.
- Nearly all recharge to the river aquifer is Colorado River water. Recharge from less than 3 inches per year of precipitation is negligible because little or no water penetrates below the soil zone (Olmsted and others, 1973, p. 72). Water from the only major tributary, the Gila River, is primarily return flow from the application of Colorado River water for irrigation upstream from Dome except during years of high flow. All flow passing through the Gila River canyon, upon entry into the Yuma area, commingles with water from the Colorado River and becomes Colorado River water.
- River water that seeps downward from unlined canals and irrigated fields creates and maintains local ground-water mounds in the river aquifer that store river water above river level.
- Wells yield water that will be replaced by water from the Colorado River or by river water stored above river level.

Legal Framework

The Colorado River Compact of 1922 apportions the waters of the Colorado River between the upper basin States and the lower basin States (U.S. Congress, 1948, p. A17–A22). The requirement for participation of the U.S. Geological Survey and the Bureau of Reclamation is stated in Article V:

> The chief official of each signatory State charged with the administration of water rights, together with the Director of the United States Reclamation Service and the Director of the United States Geological Survey shall cooperate, ex-officio:
>
> (a) To promote the systematic determination and coordination of the facts as to flow, appropriation, consumption, and use of water in the Colorado River Basin, and the interchange of available information in such matters.

Water from the mainstream in the lower Colorado River is apportioned among the States of California, Arizona, and Nevada by the Boulder Canyon Project Act of December 21, 1928 (U.S. Congress, 1948, p. A213–A225) and confirmed by the U.S. Supreme Court decree, 1964, *Arizona v. California*, in terms of consumptive use. The decree is specific about the responsibility of the Secretary of the Interior to account for consumptive use of water from the mainstream; consumptive use is defined to include "water drawn from the mainstream by underground pumping." Article V of the decree (U.S. Supreme Court, 1964) states in part:

The United States shall prepare and maintain, or provide for the preparation and maintenance of, and shall make available, annually and at such shorter intervals as the Secretary of the Interior shall deem necessary or advisable, for inspection by interested persons at all reasonable times and at a reasonable place or places, complete, detailed and accurate records of: * * *

* * * (B) Diversions of water from the mainstream, return flow of such water to the stream as is available for consumptive use in the United States or in satisfaction of the Mexican treaty obligation, and consumptive use of such water. These quantities shall be stated separately as to each diverter from the mainstream, each point of diversion, and each of the States of Arizona, California, and Nevada; * * *

Article I of the decree defines terminology and states in part:

(A) "Consumptive use" means diversions from the stream less such return flow thereto as is available for consumptive use in the United States or in satisfaction of the Mexican treaty obligation;

(B) "Mainstream" means the mainstream of the Colorado River downstream from Lee Ferry within the United States, including the reservoirs thereon;

(C) Consumptive use from the mainstream within a state shall include all consumptive uses of water of the mainstream, including water drawn from the mainstream by underground pumping, and including but not limited to, consumptive uses made by persons, by agencies of that state, and by the United States for the benefit of Indian reservations and other federal establishments within the state; * * *

Purpose and Scope

This report documents the modifications to the accounting-surface method for use in identifying wells downstream from Laguna Dam that are presumed to yield water that will be replaced by water from the Colorado River. The accounting-surface method is a tool the Bureau of Reclamation can use to identify users of Colorado River water and from which to build a policy to account for consumptive use of water from wells. The report delineates the river aquifer in the Yuma area in Arizona and California and in southeast Imperial Valley in California (fig. 1); describes the source and movement of water in the river aquifer; and describes the sediments and sedimentary rocks that transmit and store the water. The report also describes the generation of an accounting surface and contains an index map (fig. 2) and two maps (pls. 1–2) that show the approximate boundaries of the river aquifer, the generalized surface extent of the sediments and sedimentary rocks that form the river aquifer, and the configuration and elevation of the accounting surface. A map is included in the report (pl. 3) that shows the elevation and configuration of the water table outside the flood plain in California. The report presents the results of gravity studies made to determine extent and thickness of low-density sediments of the river aquifer in three localities.

Data Collection

The U.S. Geological Survey collected hydrologic data for the study from 1997 to 1999 in Arizona and California. The study area includes the lower Colorado River drainage area that extends from Laguna Dam to the international boundary with Mexico and parts of the lower Gila River drainage area and southeast Imperial Valley (fig. 1). Most of the field work was done on the alluvial slopes in southeast Imperial County, California, and on the flood plain of the lower Gila River and adjacent alluvial slopes in Arizona (pls. 1–2) where data were needed to locate the boundary of the river aquifer. The work included a well inventory, test-well drilling, and gravity studies. Annual data in this report are based on the calendar year.

Data were collected at wells near and northwest of the All-American Canal to delineate the ground-water mound. Static water levels were measured where owners permitted access to the wells and measuring instruments could be inserted into the well. Multiple measurements were made in many wells because the ground-water flow system is dynamic; water levels fluctuated as much as 6 feet during the study period. All well data are stored in a data base of the Arizona District of the

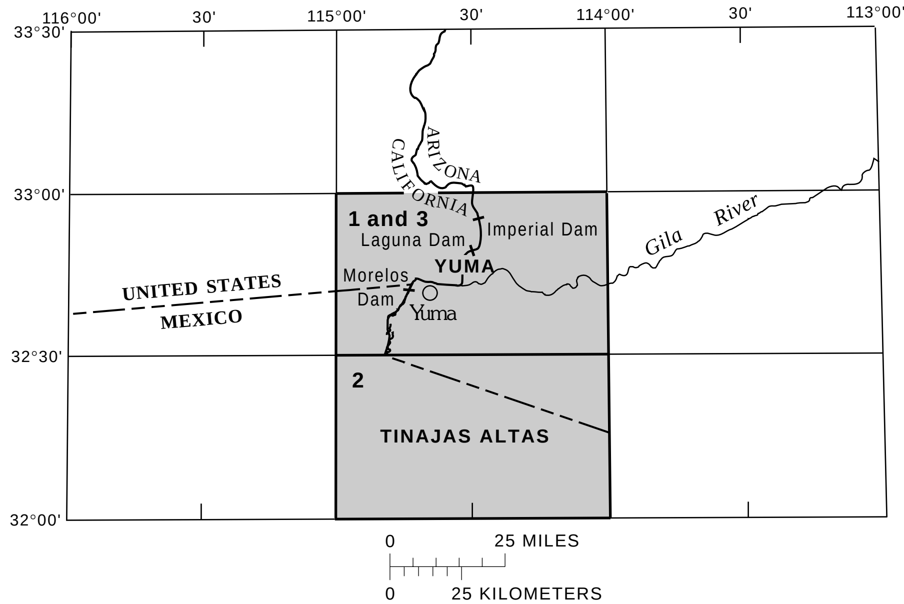


Figure 2. Index to maps of the river aquifer and accounting surface in the lower Colorado River valley and southeast Imperial Valley, plates 1–3.

U.S. Geological Survey, Tucson, Arizona. Data for wells in California also are stored in a data base of the California District of the U.S. Geological Survey, Sacramento, California.

Global Positioning System geodetic receivers were used in differential mode to survey the latitude, longitude, and elevation of wells and gravity stations (Remondi, 1985). A base station was established using four stations in a National Geodetic Survey High Accuracy Reference Network and five first-order benchmarks. Positions of all surveyed points were determined from network adjustments that included all the reference stations.

All land-surface or water-surface elevations in this report are referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 1929). All geographic positions are referenced to North American Datum of 1927 (NAD of 1927). Positions and elevations of points obtained by use of the Global Positioning System were converted to these datums by the program Corpscon (U.S. Army Topographic Engineering Center, 1997).

Test Wells

The Bureau of Reclamation drilled, logged, and completed seven test wells (A, B, C, D, E, F, and G; pl. 3) in southeast Imperial County, California, and four test wells (R, S, T, and U; pl. 3) near Dome, Arizona, as part of this study. The wells were drilled to determine extent and relation among stratigraphic units of the river aquifer to a depth of about 200 feet below river level, measure integrated static head in the upper few hundred feet of the aquifer, and provide ground truth for gravity modeling. Four of the wells in California penetrated the entire thickness of the river aquifer and bottomed in consolidated bedrock.

The U.S. Geological Survey designated drilling sites, well design, and well completion; collected drill cuttings; and determined subsurface stratigraphy from examination of cuttings and interpretation of geophysical logs. The wells were constructed to measure integrated static head to better define large changes in the ground-water flow system. Piezometers provide an accurate measurement of static head at the point in the aquifer where the piezometer is open, but integrated static-head values are needed to evaluate changes in the flow system caused by large withdrawals or movements of water. Production wells that withdraw water for irrigation or other large-scale uses commonly are open to more than 100 feet of the aquifer. The test wells were constructed of corrosion-resistant material to monitor change in static head for at least 50 years and provide long-term continuity of records.

Gravity Studies

Gravity studies were done in southeast Imperial County and in the Gila River canyon to delineate subsurface barriers to ground-water flow and to estimate extent and thickness of low-density sediments of the river aquifer. Gravity was measured at more than 350 stations and combined with the El Centro section of the Arizona State Gravity Data Base (The University of Arizona Department of Geosciences, written commun., 1993). The base station used in this study was Yuma-49 at the Yuma International Airport, which has a published gravity value of 979,515.18 milligals (mGals). Many stations in the data base have multiple values of gravity that differ significantly. These multiple values probably are due to different values being used for base stations in previous surveys. Gravity values that appeared to be consistent with those collected during this study were incorporated into this analysis.

Gravity data were reduced to complete-Bouguer anomaly values. The gravimeter readings were corrected for solid Earth tides and instrumental drift. The observed gravity values were adjusted for latitude, elevation, Bouguer slab density (2.67 grams per cubic centimeter [g/cm^3]), curvature of the Earth, and terrain. Terrain corrections were made for radial distances from each station from 175 to 32,000 feet using 7.5-minute digital-elevation models that were available for all of the area and the program TCINNER (Cogbill, 1990). Gravity-station locations were chosen to eliminate or minimize terrain effects within a radius of 175 feet from the station. Mexican digital-elevation models were obtained but were not in a form that could be used with the terrain-correction model. The terrain corrections near the international boundary with Mexico using the United States digital-elevation models were small, and the range in land elevation in Mexico within 32,000 feet of any of the gravity stations is minimal. The terrain corrections for the 10 gravity stations near the international boundary with Mexico were set to 0.0.

The gravity meter used was a LaCoste & Romberg “D” meter. The meter was calibrated at the National Geodetic Survey calibration line that extends from the Colorado School of Mines in Golden, Colorado, to Mount Evans, Colorado. Calibration was within 0.03 percent over the 500-milligal range of the fine screw and counter of the instrument. The portion of the calibration line used encompasses the values in the study area in absolute gravity values, so no coarse-screw adjustment was needed or made between calibration and completion of the study.

Thickness of alluvium can be estimated using gravity methods because gravity values are inversely related to the thickness of low-density sediments, such as alluvium, that overlie higher density igneous, metamorphic, and consolidated sedimentary rocks. Gravity values are relatively lower in the middle of intermontane basins where the thickness of alluvium is greatest and are higher at the edges of the basins.

Patterns of low-gravity values in the areas of interest can be simulated as resulting from lateral changes in thickness of low-density rocks using theoretical-gravity models. The underlying assumptions are (1) that variations in density within the alluvium are small compared with the contrast in density between alluvium and underlying consolidated rocks, (2) the contrast in density between alluvium and consolidated rock is caused by differences in porosity rather than mineralogy of the alluvial matrix, and (3) the effect of variations in density of the underlying consolidated rocks on gravity values at the land surface is spread over a large area compared to local variations in gravity values that result from variations in thickness of the alluvium. Gravity models of the subsurface geology were constructed for each of the areas of interest to simulate the thickness and extent of low-density sediments. A two-dimensional gravity model, Gmodel (LaCoste & Romberg, written commun., 1998), was used to simulate the gravity distribution along profiles. The complete-Bouguer anomaly values calculated for the gravity data-collection points were merged with the existing U.S. Geological Survey gravity data base.

Previous Investigations

Previous detailed geohydrologic studies of the Yuma area downstream from Laguna Dam and of

Imperial Valley defined and described the formations that constitute the river aquifer of this report, determined subsurface occurrence and continuity of the sediments and sedimentary rocks that fill the Salton Trough in the Yuma area and Imperial Valley in the United States and Mexicali Valley in Mexico, and discussed the regional geologic structures and framework (Olmsted and others, 1973; Loeltz and others, 1975; Olmsted, 1973). Dillon (1975) mapped bedrock of the Cargo Muchacho and Chocolate Mountains and some outcrops of the Bear Canyon fanglomerate. Eberly and Stanley (1978) described the stratigraphy and origin of some late Tertiary rock units that were deposited in the present basins of the study area and form a part of the river aquifer. Spencer and Patchett (1997) clarified the origin and depositional environment of the Bouse Formation.

Detailed hydrologic studies in the Yuma area and reconnaissance studies in Imperial Valley demonstrated the occurrence of ground water in an aquifer within the sediments and sedimentary rocks that fill the Salton Trough (Brown and others, 1956; Olmsted and others, 1973; Loeltz and others, 1975). These studies also delineated hydraulic connection between the river, drainage ditches, and wells in the younger alluvium and between the younger and older alluvium. Estimates of surface and subsurface tributary inflow downstream from Hoover Dam were compiled by Owen-Joyce (1987).

Acknowledgments

Special appreciation is extended to the well drillers, landowners, and Indian tribes of the area who provided well records and access to their property. The Bureau of Reclamation provided Global Positioning System equipment for field operations. Irrigation districts, municipal utilities, water companies, and mining companies provided well records and allowed access to their wells. Imperial County in California provided well logs. Imperial Irrigation District provided water levels and maps for their wells in southeast Imperial Valley. Wellton-Mohawk Irrigation and Drainage District and Arizona Department of Transportation granted permission to drill and construct wells on their property. Dennis Laybourn, American Girl Mining Joint Venture, and Dan Purvance, Glamis Imperial Corporation, arranged access and provided well and hydrologic information. Bart Stewart, Hydrogeophysics, did the corrections for terrain and curvature of the Earth for the gravity study.

METHOD TO IDENTIFY WELLS

The accounting-surface method can be used in the area downstream from Laguna Dam outside the flood plain of the Colorado River to identify wells that are presumed to yield water that will be replaced by water from the river, and wells that are presumed to yield water that will be replaced by river water stored above river level. The identification is made by determining the static water-level elevation in the well and comparing it to the elevation of the accounting surface at the well. Delineation of the subsurface boundaries of the river aquifer and generation of an accounting surface were required to make use of the accounting-surface method for the area downstream from Laguna Dam. The accounting surface represents the elevation and slope of the unconfined static water table in the river aquifer outside the flood plain of the Colorado River that would exist if the river were the only source of water to the river aquifer. The accounting surface was generated by using water-surface profiles of the Colorado River from Laguna Dam to about the downstream limit of perennial flow at Morelos Dam. The accounting surface extends outward from the edges of the flood plain to the subsurface boundary of the river aquifer (fig. 3). Water pumped from wells on the flood plain, including the limotrophe section, is presumed to be Colorado River water.

Wells that have a static water-level elevation equal to or below the accounting surface are presumed to yield water that will be replaced by water from the Colorado River (fig. 3, wells labeled R). The water-table elevation in the river aquifer near a well or well field is assumed to be the same as the elevation of static water levels in the wells. Pumping water from a well completed in the river aquifer where the elevation of the static water level in the well is below the elevation of the accounting surface eventually will cause the slope of the hydraulic gradient between the river and the well to be downward toward the well. This, in turn, will

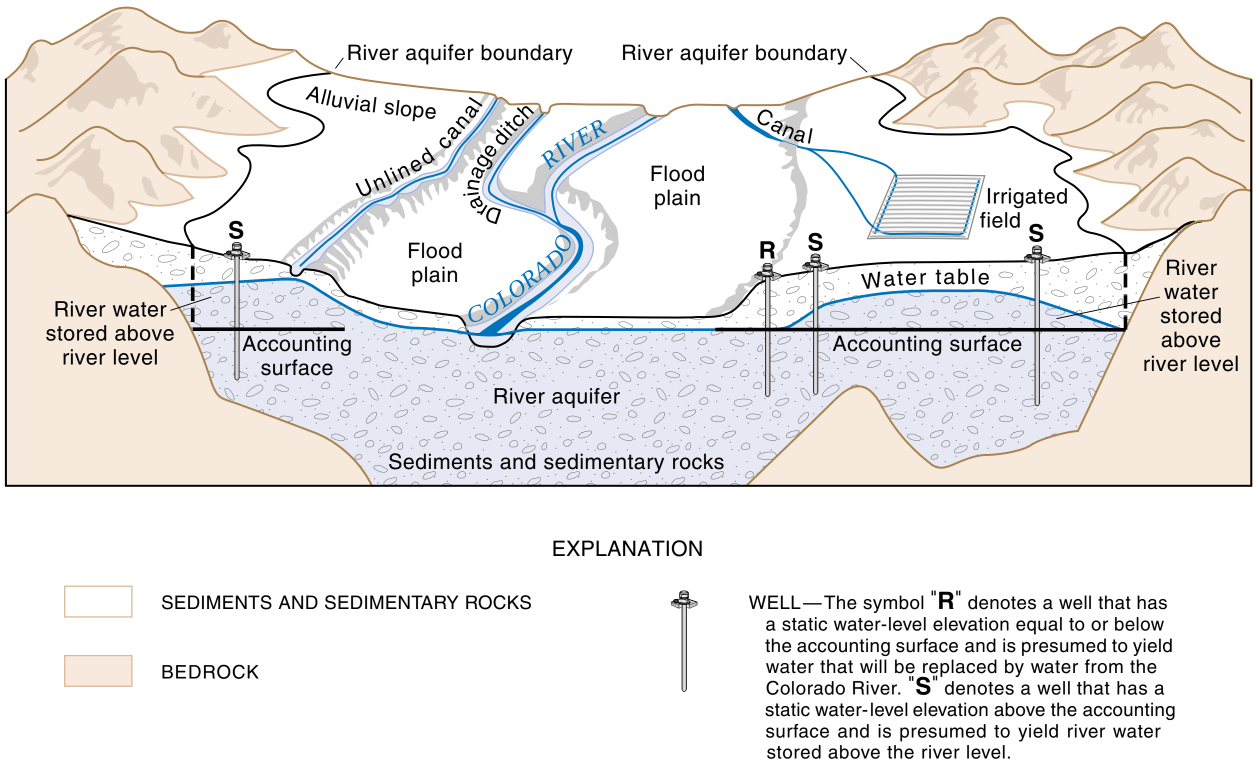


Figure 3. Schematic diagram showing the river aquifer and accounting surface.

result in the movement of water from the Colorado River into the river aquifer.

The modification to the accounting-surface method for use downstream from Laguna Dam is in the designation of the source of the water in wells where the static water level is above the accounting surface. Wells that have a static water-level elevation above the accounting surface are presumed to yield river water stored above river level (fig. 3, wells labeled S). In an area underlain by a ground-water mound, the water-level elevation in a well can remain above the accounting surface as long as river water stored above river level can move to the well to replace river water removed from storage. If more water is pumped from a well than can be replaced by river water stored above river level, the static water-level elevation in the well will decline below the accounting surface and water will eventually move from the Colorado River into the river aquifer toward the well. In an area where a well has a static water level below the accounting surface but where a ground-water mound exists between that well and the river upstream from Morelos Dam, water pumped from that well is presumed to be replaced by river water stored above river level until the mound is depleted. When the mound of river water stored above river level no longer exists, water eventually will move from the Colorado River into the river aquifer toward the well and the well will be presumed to yield water that will be replaced by water from the Colorado River.

Application of the accounting-surface method will require identification of all wells within the river aquifer from which water is pumped for consumptive use. Static water levels need to be measured and compared to the accounting surface for the method to be applied. The inventory of each well will include interviewing the well owner or operator to collect current ownership and historical information to enable the tracking of the driller's log. Other data to be collected during an inventory include determining the precise location and elevation by using a Global Positioning System and photographing the well to help with identification for future monitoring of static water levels. Bureau of Reclamation management responsibilities include a legal mandate to ensure that all diversions of Colorado River water, including those by wells, are authorized.

RIVER AQUIFER

The river aquifer consists of permeable sediments and sedimentary rocks that are hydraulically connected to the Colorado River so that water can move between the river and the aquifer in response to withdrawal of water from the aquifer or differences in water-level elevations between the river and the aquifer. The subsurface limit of the river aquifer is the nearly impermeable bedrock of the bottom and sides of the basins that underlie the Yuma area and adjacent valleys and is a barrier to ground-water flow. Delineation of the subsurface boundaries of the river aquifer was required to make use of the accounting-surface method for the area downstream from Laguna Dam.

The river and the underlying and adjacent river aquifer form a complex, hydraulically connected ground-water and surface-water flow system in the Yuma area downstream from Laguna Dam (fig. 1). Water stored in upstream surface reservoirs is delivered for use downstream from Laguna Dam. Millions of acre-feet of water are diverted or pumped annually from the river channel; most is transported for use in Imperial and Coachella Valleys through the All-American Canal downstream from Pilot Knob and for use in the lower Gila River Valley upstream from Dome through the Gila Gravity Main and Wellton-Mohawk Canals. The rest is used for irrigation of fields adjacent to the river and for municipal use in the Yuma area. Downstream from Laguna Dam, water also is stored in the river aquifer and is pumped from wells for irrigation, municipal, and domestic use. Much of the irrigation water is transpired by vegetation or evaporates, and the remainder percolates below the root zone into the river aquifer. Some of the water in the river channel, canals, and marshes percolates through the underlying soils and sediments and recharges the river aquifer. Small quantities of runoff that originate from precipitation infiltrate the beds of washes and intermittent tributary streams; most of the infiltrated water later evaporates or is transpired leaving little to recharge the river aquifer (Olmsted and others, 1973, p. 72). Ground water flows downgradient through the river aquifer and discharges as seepage into drainage ditches or through the river banks into the river. Water moves back and forth between the surface-water and ground-water systems in response to application of water to irrigated fields and annual changes in the water-level elevation of the river. Dewatering wells are used to manage ground-water levels beneath irrigated areas by withdrawing ground water for discharge to the Colorado River. Water is pumped from thousands of wells completed in the river aquifer on the flood plain, on alluvial slopes, and in tributary valleys. Agricultural development, degradation of the river channel because of reduced sediment load, and diversions upstream have caused the Colorado River to become a drain in the Yuma area (Loeltz and Leake, 1983). Agriculture is the principal economy and is possible only with irrigation. The river channel from Laguna Dam to Pilot Knob wasteway normally conveys seepage and flow from drainage ditches. Except for occasional discharge of water past Morelos Dam as a result of deliveries to Mexico in excess of treaty requirements, the channel downstream from Morelos Dam normally conveys seepage and discharge from the Main Outlet Drain Extension or is dry.

Source of Water in the River Aquifer

Water stored in upstream surface reservoirs of the Colorado River is delivered for use downstream from Laguna Dam. The Colorado River is the source for virtually all recharge to the river aquifer downstream from Laguna Dam. Most of the water in the river aquifer originated from the river because of the hydraulic connection to the river and the overbank flow that occurred before the dams were built. Ratios of hydrogen and oxygen isotopes in ground water from wells in the Colorado River valley upstream from Laguna Dam indicate that most of the water in the river aquifer beneath the flood plain originated from the river and that, in many places, river water extends from the flood plain for a considerable distance beneath the alluvial slopes (Robertson, 1991). Precipitation and inflow from tributary valleys contribute some water to the river aquifer.

Tributaries are defined in the decree as "* * *all stream systems the waters of which naturally drain into the mainstream of the Colorado River below Lee Ferry." Unmeasured tributary inflow consists of surface-water and ground-water inflow to the flood plain of the Colorado River or to the river and reservoirs from various tributary areas. The Gila River is the only significant tributary to the Colorado River downstream from Laguna Dam that provides some surface flow and ground-water underflow. Tributary waters are accountable as Colorado River water under the decree upon entry into the mainstream of the Colorado River. Estimates and areal distribution of tributary inflow to the lower Colorado River were summarized by Owen-Joyce (1987).

Colorado River

The principal source of water to the area downstream from Laguna Dam is the Colorado River, although much of the water does not arrive in the river channel (table 1). The total surface inflow that arrives at Imperial Dam is calculated for the streamflow-gaging station Colorado River above Imperial Dam, which is 5 miles upstream from Laguna Dam (pl. 1). The mean annual flow upstream from Imperial Dam was about 8.2 million acre-feet for 1977–98 (table 1). At Imperial Dam, most of the water is diverted from the river into the All-American Canal on the California side of the river and into the Gila Gravity Main Canal on the Arizona side; flow remaining in the Colorado River channel downstream from Imperial Dam is measured at the streamflow-gaging station Colorado River below Laguna Dam (fig. 4). The Colorado River gains flow from Laguna Dam to Morelos Dam (table 1) because the river functions as a drain and collects irrigation drainage, inflow from the Gila River, and releases of Colorado River water from the All-American Canal through the Yuma Main Canal and Pilot Knob wasteways (fig. 5). Additional flows in the Colorado River downstream from Laguna Dam occur when excess water from flood-control releases from upstream reservoirs arrives at Imperial Dam and exceeds the diversion capacity of the All-American Canal. Flow that arrives in the channel of the Colorado River at the northerly international boundary streamflow-gaging station is most of the water delivered in satisfaction of the treaty obligation to Mexico. Mexico diverts the water from the river at Morelos Dam. Downstream from Morelos Dam, the river is usually dry except for irrigation return

Table 1. Annual flow at streamflow-gaging stations on the Colorado River and associated canals, 1977–98

Site number[1]	Station number	Station name	Annual flow 1977–98, in acre-feet		
			Minimum	Maximum	Mean
1	09429490	Colorado River above Imperial Dam	4,760,000	19,110,000	8,241,000
2	09429500	Colorado River below Imperial Dam	230,800	8,431,000	1,361,000
3	09529600	Colorado River below Laguna Dam	243,900	10,250,000	1,824,000
6	09521100	Colorado River below Yuma Main Canal wasteway at Yuma	534,800	10,590,000	2,582,000
7	09522000	Colorado River at northerly international boundary above Morelos Dam	1,385,000	15,430,000	4,430,000
8	09522500	Gila Gravity Main Canal near Imperial Dam	654,500	891,500	776,900
9	09522700	Wellton-Mohawk Canal	286,800	448,900	391,800
10	09522850	Gila Gravity Main Canal at pumping plant	221,610	279,600	251,200
11	09523000	All-American Canal near Imperial Dam	3,846,000	8,368,000	5,682,000
12	09527000	Pilot Knob Powerplant and wasteway near Pilot Knob[2]	98,840	4,865,000	1,785,000
13	09527500	All-American Canal below Pilot Knob wasteway	2,865,000	3,492,000	3,222,000

[1]Locations plotted on plate 1.

[2]Flow returned to river for delivery to Mexico at Morelos Dam.

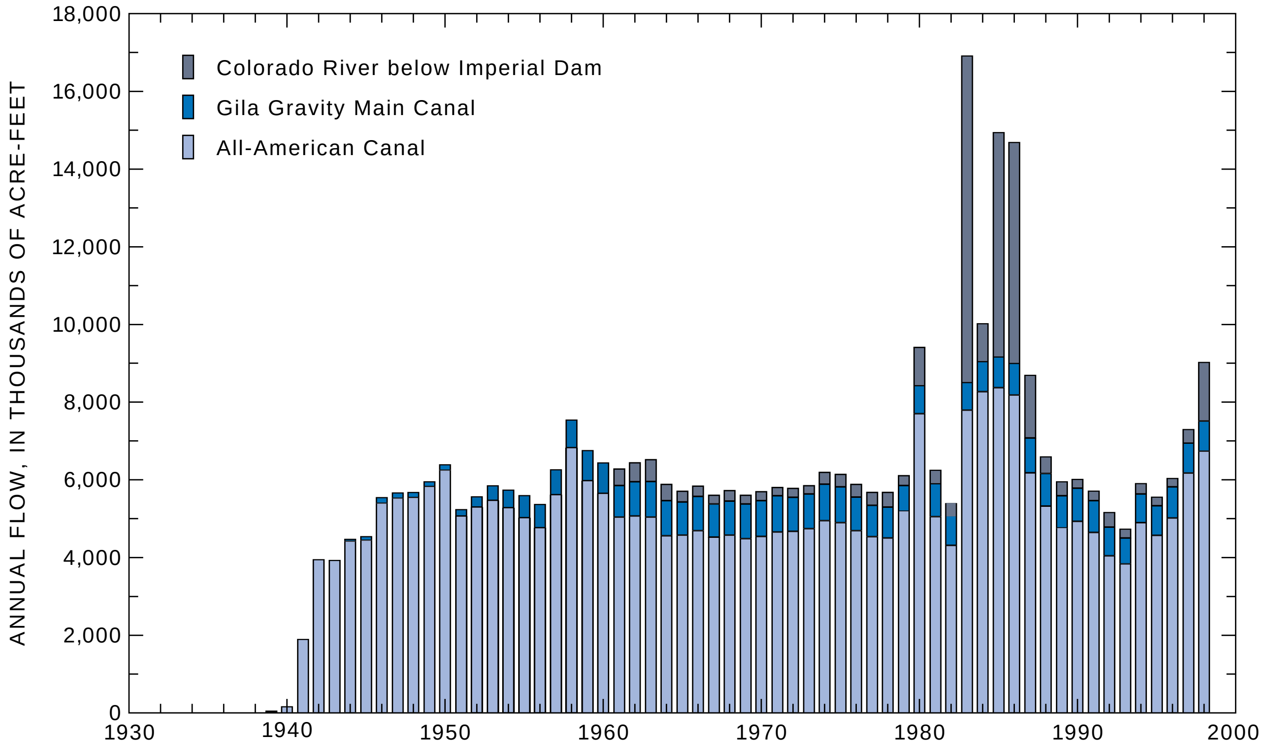


Figure 4. Annual flow in the Colorado River above Imperial Dam. This flow is the sum of flow diverted from the Colorado River into the All-American Canal near Imperial Dam, 1938–98, flow diverted into the Gila Gravity Main Canal, 1944–98, and flow in the Colorado River below Imperial Dam, 1961–98.

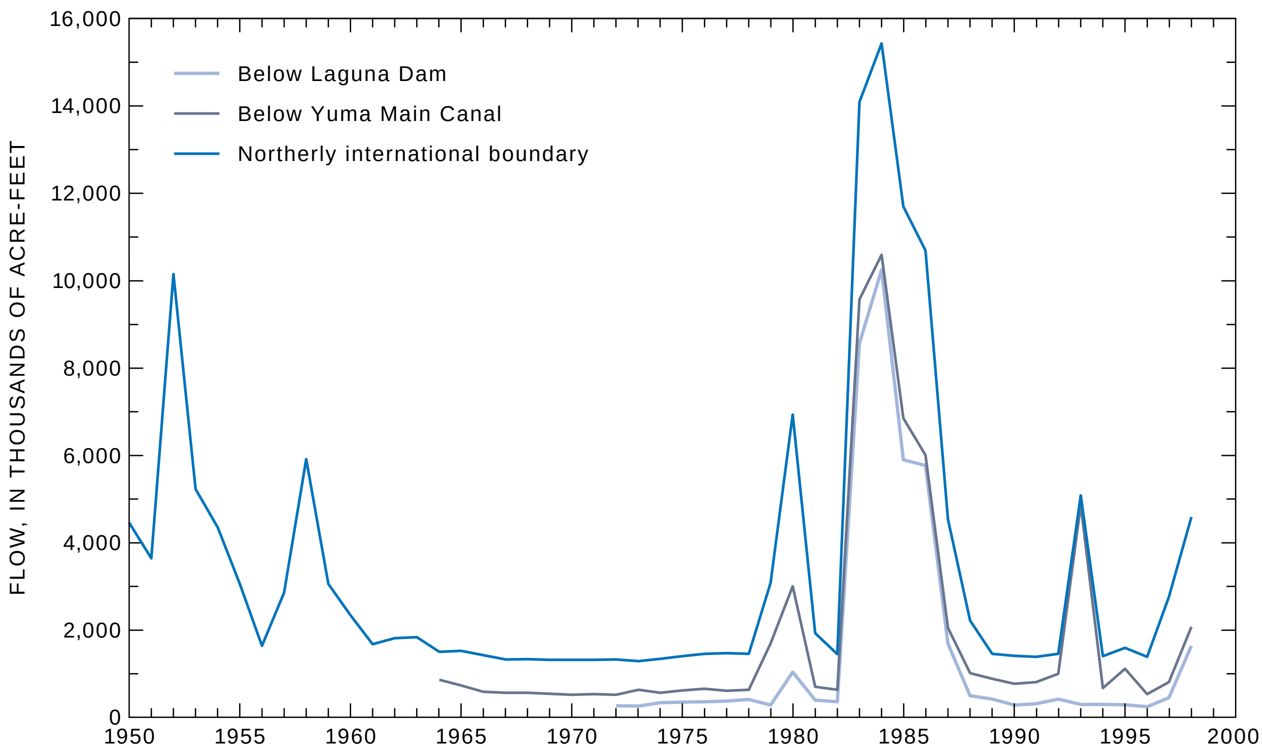


Figure 5. Annual flow in the Colorado River below Laguna Dam, 1972–98, below Yuma Main Canal, 1964–98, and at the northerly international boundary, 1950–98.

flows in short reaches or during flood-control releases from upstream reservoirs.

Part of the water diverted into the canals at Imperial Dam is exported out of the Yuma area. About 60 percent of the flow diverted into the All-American Canal is exported to Imperial and Coachella Valleys in California downstream from Pilot Knob wasteway; 28 percent is returned to the river through the powerplant and wasteway for delivery to Mexico; and 12 percent is used for irrigation on the Colorado River flood plain in California and Arizona, for the City of Yuma's public supply, or returns to the river. About 51 percent of the flow diverted into the Gila Gravity Main Canal is exported to Arizona upstream from Dome along the Gila River in the Wellton-Mohawk Canal; 32 percent is delivered for use on Yuma Mesa at the pumping plant (table 1); and 17 percent is used for irrigation on the flood plains of the Colorado and Gila Rivers downstream from Dome in Arizona or returns to the river. For this report, Yuma Mesa collectively refers to the area designated Yuma and Upper Mesas in Olmsted and others (1973, fig. 2).

Gila River

Flow in the Gila River is measured at a streamflow-gaging station near Dome, about 12 miles upstream from the mouth (pl. 1), to monitor inflow from the Gila River Basin where it enters the Yuma area. Flow is highly variable because of regulation by reservoirs and many diversions for irrigation upstream from the streamflow-gaging station. Annual flow ranged from 0 to 4,732,000 acre-feet between 1903 and 1998 (fig. 6); after 1950, which generally corresponds with the start of delivery in 1952 of Colorado River water in the Wellton-Mohawk Canal, there has been flow all year at Dome. Flow measured near Dome consists of two components—Gila River water (tributary inflow) and return flow from upstream irrigation with Colorado River water mainly on the flood plain upstream from Dome.

Mean annual flow calculated for 1977–98 at three streamflow-gaging stations along the Gila River shows that the river loses flow (table 2). Flow at the streamflow-gaging station below Painted Rock Dam, 100 miles upstream from the Dome streamflow-gaging station, is tributary water.

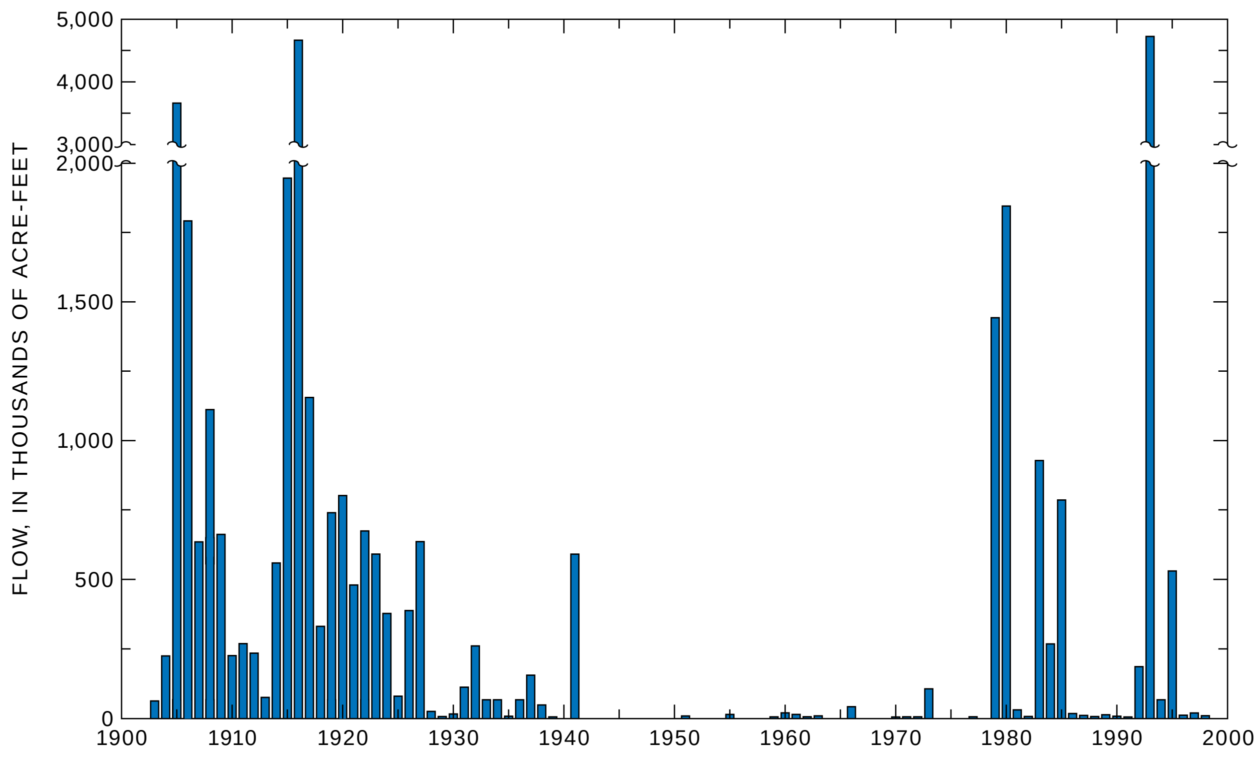


Figure 6. Annual flow in the Gila River near Dome, 1903–98.

Table 2. Annual flow at streamflow-gaging stations on the Gila River, 1977–98

Site number[1]	Station number	Station name	Miles upstream from Gila River near Dome	Annual flow 1977–98, in acre-feet		
				Minimum	Maximum	Mean
([2])	09519800	Gila River below Painted Rock Dam	100	201	5,088,000	607,000
([2])	09520360 09520280	Gila River near Mohawk and Gila River near Dateland[3]	65	0	4,596,000	511,300
4	09520500	Gila River near Dome	0	774	4,732,000	495,300

[1]Locations plotted on plate 1.

[2]Located outside the plate borders and study area.

[3]Combined flow data for Gila River near Mohawk 1977–93 and Gila River near Dateland 1994–98.

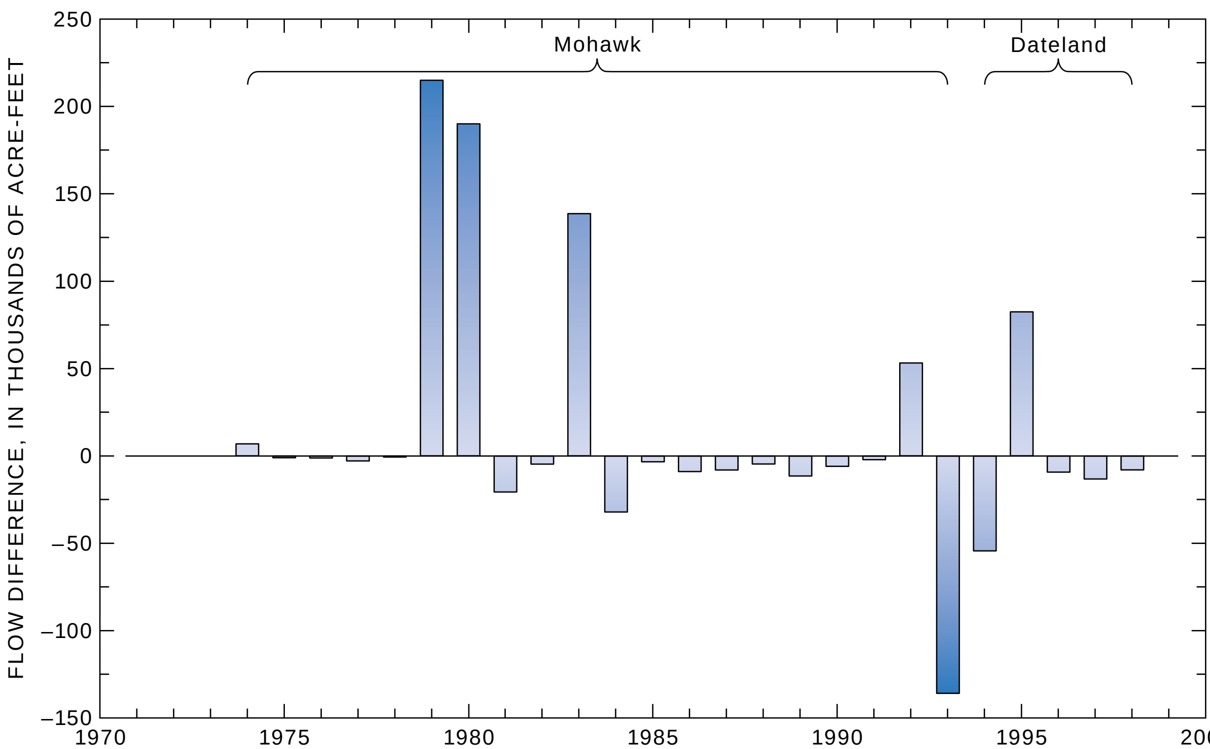


Figure 7. Difference in annual flow between the Gila River near Mohawk, 1974–93, or the Gila River near Dateland, 1994–98, and flow in the Gila River near Dome.

Flow measured in the Gila River near Mohawk (1977–93) and in the Gila River near Dateland (1994–98), 65 miles upstream from Dome, and the area irrigated with Colorado River water from the Wellton-Mohawk Canal also is considered tributary water. The difference in flow between the Mohawk or Dateland and Dome streamflow-gaging stations is influenced by seepage from the Gila River into the alluvium when flows are high, subsequent returns from bank storage when high flows recede, runoff from the intervening 2,420 square miles of drainage area, and irrigation return flows from applied Colorado River water (fig. 7). Beginning in 1951, minimum flows near Mohawk or Dateland have been zero. In contrast, the Gila River near Dome is perennial. The mean annual flow (table 2) indicates a losing reach downstream from Mohawk/Dateland; however, annual differences in flow (fig. 7) indicate that the Gila River gains flow in more years than it loses flow. Major losses in

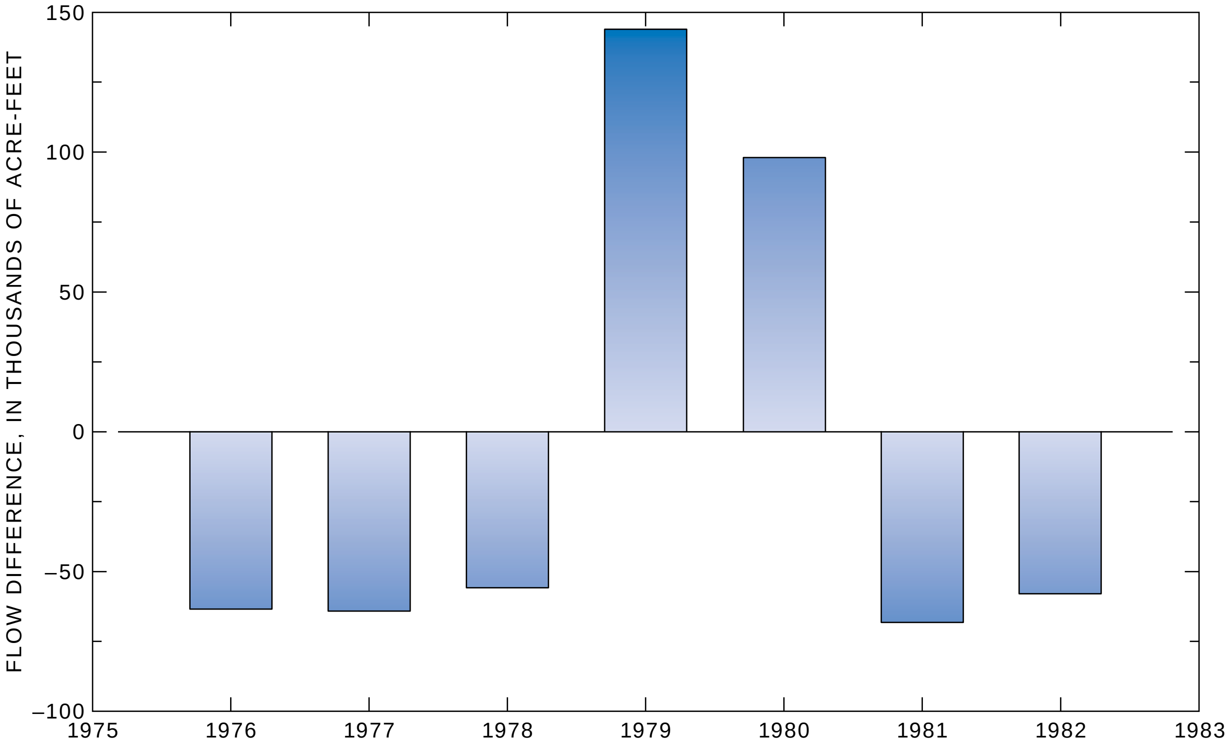


Figure 8. Difference in annual flow between the Gila River near Dome and the Gila River near the mouth, 1976–82.

flow of the Gila River between Mohawk/Dateland and Dome during three high-flow years (1979, 1980, and 1983; fig. 7) skew the mean annual flows. Estimating the quantity of irrigation return flow from diverted Colorado River water mixed with the flow from local runoff and bank-storage returns from runoff near Dome that do not necessarily occur in the same year is not possible using only streamflow records.

Flow in the Gila River between Dome and the mouth consists of flow that originates upstream from Dome and return flow from irrigation with Colorado River water on the adjacent flood plain. During low-flow years, such as 1976–78 and 1981–82, flow near the mouth (fig. 8) is higher than that near Dome because irrigation return flow enters the reach between the streamflow-gaging stations and flows near Dome are solely irrigation return flow. During high-flow years, such as 1979 and 1980, flow near the mouth is lower than near Dome because water from the Gila River infiltrates to become bank storage and later drains once the high flows subside (Owen-Joyce and Raymond, 1996). The gain in flow as a result of irrigation return flows is easier to discern between these two stations because most local storms affect flow at both stations, and runoff is usually small in this reach.

Unmeasured Tributary Inflow

The dynamic nature of the hydrologic system makes the quantification of unmeasured tributary inflows difficult, and the quantity can be estimated only by indirect means. Unmeasured tributary inflow consists of surface-water and ground-water inflow to the flood plain of the Colorado River or to the river from various tributary areas. In previous studies, average annual quantities of unmeasured tributary inflow were estimated as a function of mean annual precipitation for 1931–60. These estimates were determined to be valid for use because mean annual precipitation for 1951–80 did not differ significantly from that of 1931–60 (Owen-Joyce, 1987). Little or no recharge to the aquifer occurs because the mean annual precipitation of less than 8 inches (Metzger and others, 1973, p. 35) throughout this area is much less than the potential evapotranspiration. Over most of the study area, mean annual rainfall is less than 3 inches. Unmeasured tributary inflow to the Colorado River downstream from Laguna Dam is small; estimated average annual unmeasured runoff is 2,000 acre-feet and unmeasured ground-water inflow near Dome is 1,000 acre-feet (Owen-Joyce, 1987, table 3), or about 0.04 percent of the mean annual flow arriving at Imperial Dam. The majority of the underflow near Dome probably is return flow from unused irrigation with Colorado River water upstream from Dome. Tributary ground-water inflow commingles with water that originated as infiltrated surface water diverted from the Colorado River in the river aquifer. Commingled waters are pumped from wells that tap the river aquifer for irrigation and for domestic and municipal use.

Subsurface Storage of Water Above Colorado River Level

Most of the water diverted from the Colorado River is transported through the Yuma area and exported out of the area west of Pilot Knob in California or east of Dome in Arizona, or is delivered to Mexico at Morelos Dam. The remainder of the diverted water is delivered by canals and applied to irrigated fields in the Yuma area where it is transpired by vegetation, evaporates, or seeps below the root zone into the river aquifer. Recharge to the river aquifer from unlined canals outside the flood plain on the mesas began in Imperial Valley in 1939 and on Yuma Mesa in 1923. Substantial ground-water mounds of recharged river water have been created in those two places. Much of the water in the mounds is stored above the water-surface elevation of the Colorado River.

Water leaking from the unlined All-American Canal during the last 60 years has recharged the river aquifer and caused major changes in the elevation and slope of the water table. Previous investigations in the 1960’s and 1980’s indicated that linear ground-water mounds had formed beneath the All-American Canal, but the configuration of the water table and directions of ground-water flow during the 1990’s were poorly known. Water-level elevations in existing wells and in test wells drilled during this study were used to delineate the 1998–99 water table (pl. 3). Where possible, measurements were made of integrated static head in the upper few hundred feet of the aquifer. A comparison of the configuration of the water table of 1998–99, to that of 1939 when the canal was first opened, was used to infer total water-level rises and change in direction of ground-water flow (Olmsted and others, 1973, fig. 28).

Before the construction of the All-American Canal in 1939, water-level elevations ranged from more than 120 feet beneath Picacho Mesa to about 65 feet along the west edge of the study area at 115 degrees west longitude (Olmsted and others, 1973, fig. 28). Ground-water was inferred to flow west from the northwest edge of the flood plain through the gap between Pilot Knob and the Cargo Muchacho Mountains toward the central part of Imperial Valley.

When water was first diverted into the canal, seepage through the unlined bottom recharged the river aquifer and ground-water mounds began to form beneath the canal. The water-level rises beneath the All-American Canal and the mesas have continued to the present (1999). The inferred total water-level rises beneath Pilot Knob Mesa range from about 40 to 60 feet near the All-American Canal, are about 40 feet near the Ogilby Hills, and are perhaps less than 10 feet near the north edge of the river aquifer at 33 degrees north latitude. The water table continues to rise a few tenths of a foot per year under much of Pilot Knob Mesa (pl. 3). Inferred water-level rises beneath Picacho Mesa are about 15 to 20 feet.

The shape of the 1998–99 water table beneath Picacho and Pilot Knob Mesas indicates a ground-water divide beneath the All-American Canal (pl. 3). The water table slopes northward and northwestward from the All-American Canal toward the edge of the river aquifer. Northeast of Pilot Knob the water table slopes southeastward toward drains in the flood plain; west of Pilot Knob it slopes southward from the All-American Canal toward Mexico. Water-level elevations beneath the All-American Canal range from about 130 to 150 feet northeast of Pilot Knob and from 101 feet to 150 feet west of Pilot Knob to 115 degrees west longitude (pl. 3).

Currently (1999), water flows from beneath the All-American Canal to the north and northwest beneath Picacho and Pilot Knob Mesas, to the southeast to the edge of the flood plain, and to the south beneath the international boundary with Mexico toward pumped wells and drainage ditches in Mexico. The gradient and rate of flow to the north is much less than that toward Mexico. In 1991, nearly all canal seepage between Pilot Knob and 115 degrees west longitude moved south toward pumping centers in Mexico (Watt, 1994).

The ground-water mound beneath Yuma Mesa began to form in 1923 when river water was pumped and delivered to 660 acres of newly irrigated land of the Yuma Auxiliary Project (Olmsted and others, 1973, table 1). The mound originated from recharge of seepage below unlined canals and irrigated fields. By 1962, the mound covered a large area beneath Yuma Mesa (Olmsted and others, 1973, figs. 38 and 40). Recharge and seepage continued after 1965 because surface water continued to be delivered to Yuma Mesa (Owen-Joyce and Raymond, 1996, fig. 24). Concurrent with growth of the mound, drainage ditches and wells were installed at the edges of the flood plain around Yuma Mesa to prevent waterlogging of the soil by water from the mound (Olmsted and others, 1973, p. H9). The mound has been maintained by recharge from seepage to the present time (1999). Drainage ditches and drainage wells continue to remove water flowing from beneath Yuma Mesa, which is returned to the river (Owen-Joyce and Raymond, 1996, p. 41 and fig. 27). Water-level changes in wells in the Yuma area are monitored by the Bureau of Reclamation. Water-table maps of the area are made available on a periodic basis (Bureau of Reclamation, Yuma Area Office, written commun., 1999).

Geologic Formations and Their Hydrologic Characteristics

The river aquifer downstream from Laguna Dam consists primarily of saturated sediments of the delta of the Colorado and Gila Rivers and some alluvium of local origin. The sediments and sedimentary rocks fill the Salton Trough, which is a tectonically active extension of the Gulf of California that extends beyond the Salton Sea into Coachella Valley in California (fig. 1). The southwest flanks of the Chocolate, Laguna, Gila, and Tinajas Altas Mountains form the northeast rim of the trough in the United States. Nearly impermeable consolidated bedrock of the mountains forms barriers to subsurface flow. Small areas of subsurface hydraulic connection are present beneath the flood plain of the Colorado River between the Chocolate and Gila Mountains at Laguna Dam and beneath the flood plain of the Gila River between the Laguna and Gila Mountains.

The lower Colorado and Gila Rivers enter the Yuma area through canyons cut between the Chocolate and Laguna Mountains and between the Laguna and Gila Mountains, respectively. Before the entrance of the Colorado River into the area, alluvium eroded from the mountains along the northeast side of the Salton Trough and formed alluvial fans and filled local basins. Most of the deltaic sediments came from the Colorado River drainage upstream from the Gila River. Sediments from the Gila River interfinger with Colorado River sediments where the Gila River enters the trough. During late Pleistocene time, the Colorado and Gila Rivers cut down into the delta and formed a valley floor about 100 to 200 feet below the modern flood plains. As sea level rose during late Pleistocene and Holocene time, river sediments of the younger alluvium were deposited in the valley and now form the modern flood plains of the two rivers.

Sediments and sedimentary rocks of the river aquifer that fill the Salton Trough are the younger alluvium, older alluvium, Bouse Formation, and conglomerate of the Chocolate Mountains (Olmsted and others, 1973). In this report, all sediments and sedimentary rocks between bedrock and the base of the younger alluvium are mapped and included with the older alluvium. In the previous study upstream from Laguna Dam, the Bouse Formation and fanglomerate of Metzger (1965) were mapped and shown separately (Wilson and Owen-Joyce, 1994). Where the two studies overlap in the Chocolate and Laguna Mountains near Laguna Dam, the upper member of the Kinter Formation of Miocene age previously was included with the fanglomerate of Metzger (1965) but herein is assigned to the bedrock.

Younger alluvium of Holocene and Pleistocene ages consists of unconsolidated gravel, sand, silt, and clay deposited on alluvial slopes and flood plains and in stream channels. The younger alluvium is the last sediment deposited by the Colorado and Gila Rivers as they meandered across the modern flood plain before the dams and diversion structures were built (Olmsted and others, 1973). Beneath the flood plain of the two rivers, the upper part of the unit is from 0 to about 180 feet thick along the Colorado River and consists of sand, silt, and clay, and the base of the unit consists mainly of sand and rounded fine gravel. Younger alluvium along the Gila River consists of moderately sorted dark gray sand and a few well-rounded pebbles of mainly dark fine-grained rocks. The unit ranges from 117 to 178 feet in thickness at test wells in sections 4 and 9, T. 8 S., R. 21 W. (G&SR) in Arizona (pl. 3). The younger alluvium of the flood plain of the Gila and Colorado Rivers is delineated on plates 1–3; outside the flood plain, the unit generally is above the water table and is mapped with the older alluvium.

Beneath the flood plains of the Colorado and Gila Rivers, the younger alluvium is the upper water-bearing unit of the river aquifer. All but the uppermost few feet of the unit is saturated. Younger alluvium is highly permeable and can yield more than 1,000 gallons per minute of water to wells. Direct runoff from occasional intense rainfall infiltrates into this unit in the stream channels of tributaries and provides a negligible recharge to the river aquifer. Many of the irrigated fields in the Yuma area are on the surface of the younger alluvium, and drainage ditches and canals are cut into it.

Older alluvium forms Yuma, Picacho, and Pilot Knob Mesas and underlies the younger alluvium of the flood plains of the Colorado and Gila Rivers (fig. 1; pl. 1). Within the older alluvium, the river sediments are Pleistocene and Pliocene in age and the alluvial units of local origin are Miocene, Pliocene, and Pleistocene (Spencer and Patchett, 1997). The major unit of the older alluvium consists of sediments that include layers and lenses of rounded gravels, sand, silt, and clay that were deposited mainly by the Colorado River; coarse-gravel, wedge, and transition zones; and the Bouse Formation (Olmsted and others, 1973). Minor units of the older alluvium include conglomerate of Chocolate Mountains (Olmsted and others, 1973) and weakly to moderately consolidated alluvium of local origin. The minor units were deposited in alluvial fans that extend from the mountains into the valleys and basins and are interbedded with the river sediments along the margin of the Salton Trough. Along the northeast edge of Picacho and Pilot Knob Mesas, locally derived alluvial fans were deposited on bedrock and underlie river sediments. During deposition of the delta, river sediments and locally derived alluvium interfingered at the edge of the flood plain. After deposition of river sediments ceased, alluvium continued to erode from the mountains and overlapped the edge of the river sediments.

The sediments of the Colorado and Gila Rivers above the Bouse Formation make up most of the river aquifer and are the most permeable layers. Potential well yields of the river sediments range from a few hundred to more than 5,000 gallons per minute and primarily depend on the thickness of layers of rounded gravels within the sediments where the layers are present or the total saturated thickness tapped by the well if the layers are absent.

The Bouse Formation of upper Miocene to Pliocene age consists of a thin basal limestone and marl overlain by clay, silt, and sand (Metzger, 1968; Spencer and Patchett, 1997). This formation is the basal unit of the deltaic sediments of the Colorado River and was deposited in seawater in the opening and subsiding Salton Trough. Upstream from Laguna Dam, the Bouse Formation also is the basal unit of the Colorado River sediments and was deposited in a chain of lakes (Spencer and Patchett, 1997). The Bouse Formation is present beneath the flood plain and Yuma Mesa in most of the study area southeast of the All-American Canal, but was not recognized in the test wells beneath Picacho and Pilot Knob Mesas. Clays and silts of the lower part of the Bouse Formation are almost impermeable; upper sandy layers are permeable and could yield perhaps tens of gallons of water per minute to wells.

The conglomerate of Chocolate Mountains (Olmsted and others, 1973) and undifferentiated older alluvium of local origin are continental alluvial gravel, sand, silt, and clay that were deposited in alluvial fans eroded from the Chocolate, Laguna, Gila, and Tinajas Altas Mountains. Clasts of the units mainly are granitic, metamorphic, or volcanic rocks and are dominated by the most common rock type of the local source area. The clasts are angular to subrounded. This material commonly is poorly sorted and weakly to moderately consolidated. Potential well yield from the units is from tens to a few hundreds of gallons per minute where the units are composed primarily of sand and gravel. Where they are silty the units may yield only a few gallons per minute.

Bedrock consists of volcanic and sedimentary rocks of Mesozoic and Tertiary ages and crystalline igneous and metamorphic rocks of Precambrian and Mesozoic ages. The Tertiary sedimentary rocks include older marine sedimentary rocks, red beds, breccia and conglomerate, the Kinter Formation (Olmsted and others, 1973), and the Bear Canyon fanglomerate of Dillon (1975). These rocks are dense, consolidated, and weakly to firmly cemented. The crystalline rocks are nearly impermeable but probably will yield a few gallons of water per minute to wells where fractured or weathered. Some of the volcanic flows and sedimentary rocks of Tertiary age probably will yield a few tens of gallons per minute to wells.

Yuma Area

The river aquifer at Laguna Dam consists of 471 feet of Colorado River sediments, including 262 feet of Bouse Formation deposited on older alluvium and bedrock. The gap between the bedrock of the Chocolate and Laguna Mountains is 1 mile wide. The permeable river sediments provide a direct connection for subsurface flow in the river aquifer upstream and downstream from Laguna Dam. Ground water flows from beneath Laguna Dam downvalley into the Yuma area.

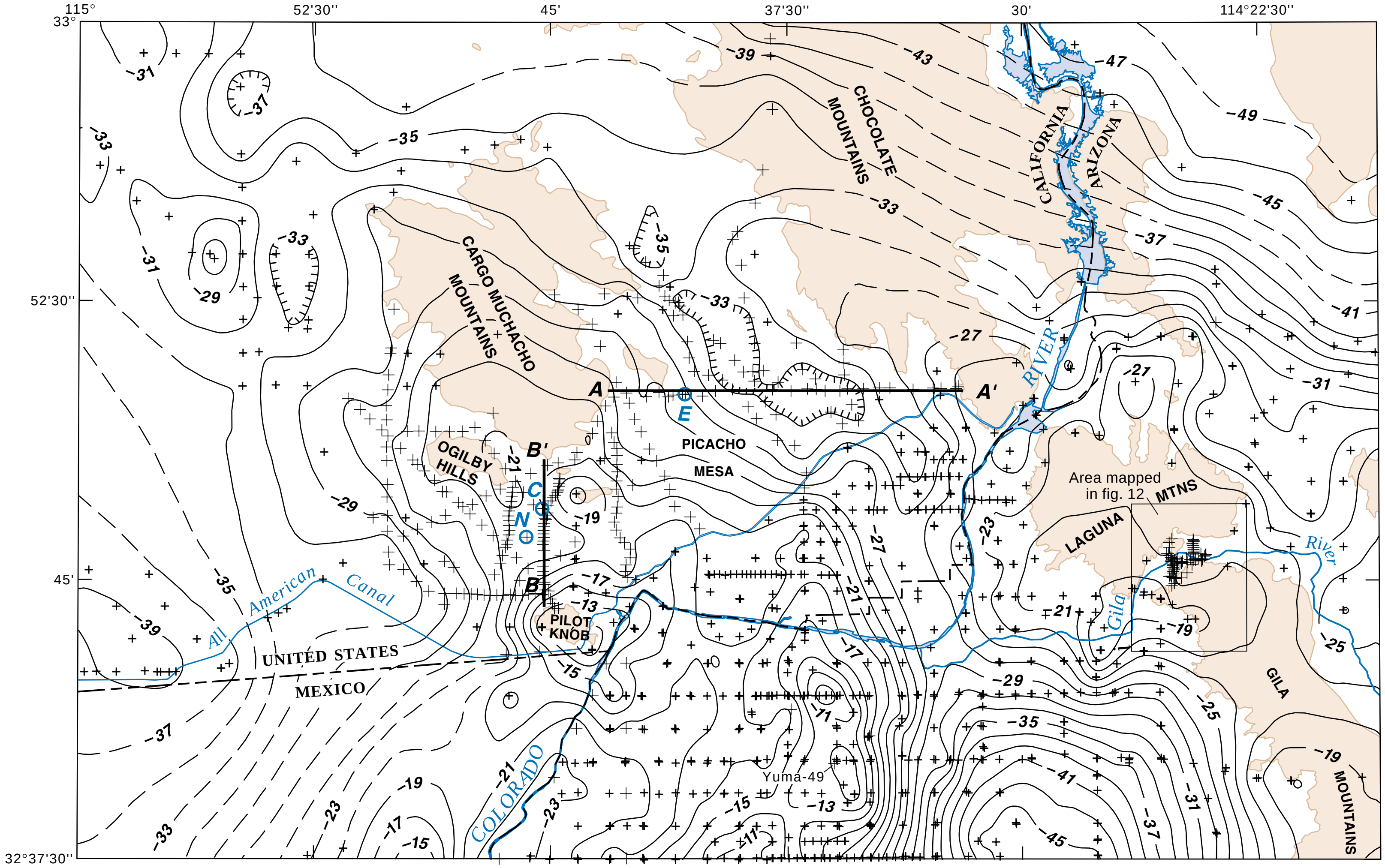
The river aquifer beneath Picacho Mesa primarily consists of Colorado River sediments that pinch out against Tertiary silt and sandy silt of local origin north of the Fort Yuma Indian Reservation (pl. 3) or against bedrock of the Cargo Muchacho and Chocolate Mountains. Nearly all of the Fort Yuma Indian Reservation is underlain by saturated river sediments. Test well E penetrated 497 feet of slightly silty Colorado River sediments overlying 67 feet of Tertiary sandy silt, which is deposited on granodiorite bedrock; 138 feet of the river sediments are saturated (pl. 3). Bureau of Reclamation test holes P and Q penetrated 566 and 800 feet of probable river sediments, respectively. Several hills of bedrock are surrounded by the aquifer. The Tertiary sediments also are saturated but potential well yields are small. Test well G on Picacho Mesa penetrated 282 feet of Tertiary sandy silt of local origin, 24 feet of local gravel and weathered bedrock, and encountered a buried bedrock hill about 171 feet above river level. The gravel and bedrock are dry. The Tertiary sediment near the buried hill probably is saturated only a few feet above river level.

The gravity study delineated a basin beneath the northern part of Picacho Mesa (fig. 9). The river aquifer thickens north of the All-American Canal. A two-dimensional gravity model was completed for the profile across Picacho Mesa (fig. 9, *A–A'*, fig. 10). An approximately 0.08-milligal-per-mile gradient was removed to give the residual gravity profile. Calibration of density for the alluvium was obtained from depth to bedrock, which was 564 feet, at test well E along the profile. The densities used in the model are 2.07, 2.27, and 2.67 g/cm^3 for unsaturated alluvium, saturated alluvium, and igneous bedrock, respectively. Simulated greatest depth to bedrock was 2,530 feet below land surface or 2,170 feet below sea level. The elevation of the water table is about 132 feet along the profile, which yields a value of about 2,300 feet for maximum saturated thickness of alluvium in the central part of the basin between the Cargo Muchacho and Chocolate Mountains.

Beneath Yuma Mesa, older alluvium that forms the river aquifer pinches out against the bedrock of the southwest side of the Gila and Tinajas Altas Mountains from the edge of the Gila River flood plain to the international boundary with Mexico. Colorado River sediments make up most of the older alluvium; small quantities of alluvium of local origin may be saturated near the bedrock outcrops of the mountains. The river aquifer surrounds the exposed bedrock of the Butler Mountains (pl. 2).

Southeast Imperial Valley

The river aquifer beneath Pilot Knob Mesa consists primarily of Colorado River sediments. Along the southwest flanks of the Chocolate Mountains and near the Cargo Muchacho Mountains, the river sediments are interbedded with and overlie alluvium of local origin. The river sediments range in thickness from 0 along the southwest flank of the Chocolate Mountains and south side of the Cargo Muchacho Mountains to more than 2,519 feet in well O. In well M, 135 feet of alluvium of local origin overlies more than 545 feet of Colorado River sediments. Sediments in the gap between the Ogilby Hills and the Cargo



Base from U.S. Geological Survey digital data, 1:100,000, 1982
Universal Transverse Mercator projection, Zone 11

0 5 MILES
0 5 KILOMETERS

EXPLANATION

SEDIMENTS AND SEDIMENTARY ROCKS

BEDROCK

–21 – – LINE OF EQUAL GRAVITY ANOMALY—Dashed where approximately located. Hachured where enclosed low. Interval 2 milligals

A —— A' TRACE OF MODELED-GRAVITY PROFILE

+ GRAVITY STATION—This study

+ GRAVITY STATION—Arizona data base

E TEST WELL AND WELL NUMBER

Figure 9. The complete-Bouguer gravity anomaly for the Yuma area, Arizona and California.

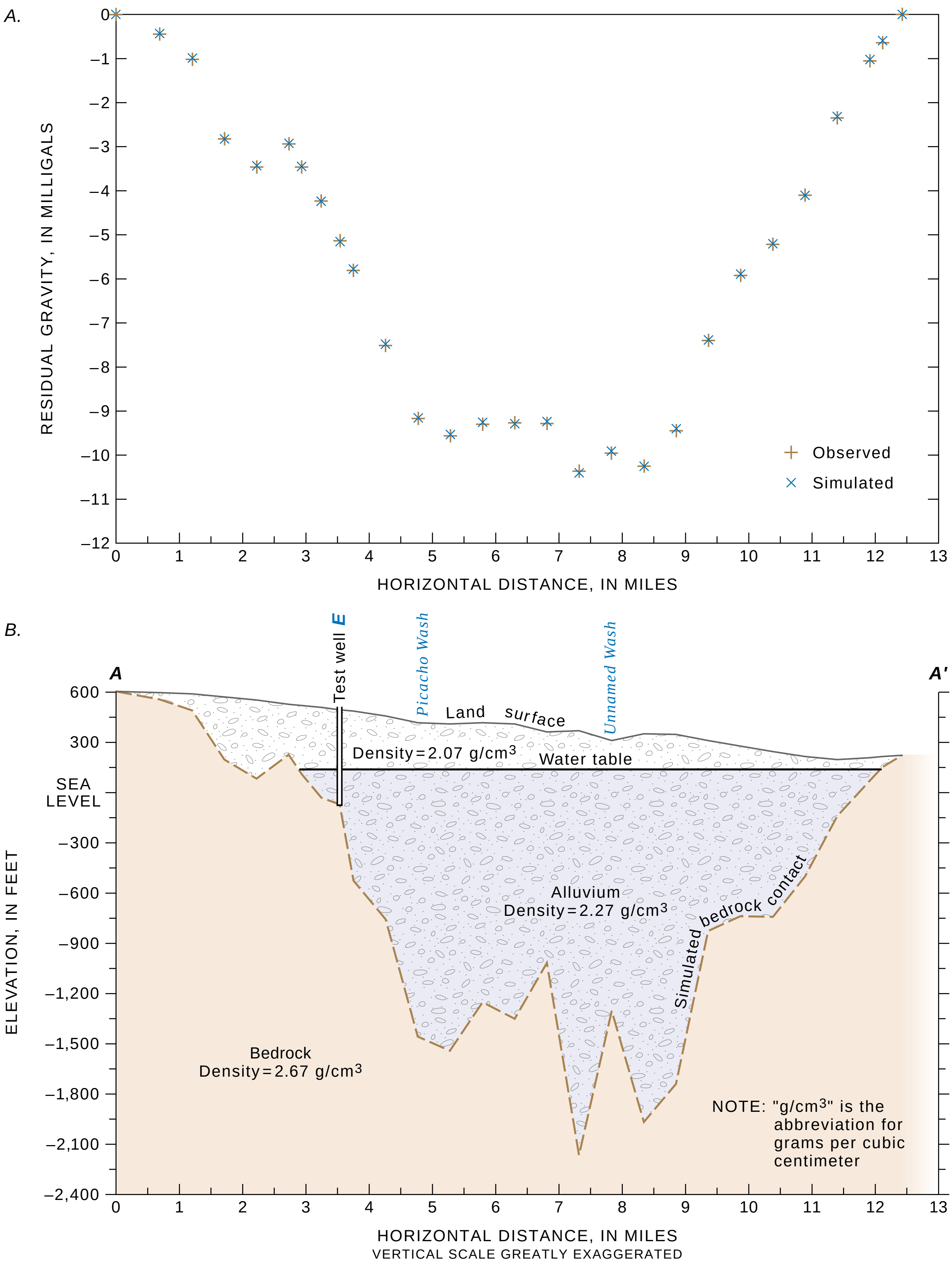


Figure 10. Observed and simulated two-dimensional gravity model for section *A–A′*, Imperial County, California. *A*, Observed and simulated residual gravity. *B*, Gravity model.

Muchacho Mountains probably are deep enough to be part of the river aquifer. Test well D penetrated 81 feet of saturated Colorado River sediments 2,000 feet southwest of bedrock outcrops of the hills. Test well C is completed in the river aquifer about 1.4 miles southeast of the hills and penetrated 460 feet of Colorado River sediments overlying 46 feet of alluvium of local origin deposited on bedrock. Test well F penetrated 543 feet of Colorado River sediments (pl. 3).

The river aquifer is continuous between Pilot Knob and the Cargo Muchacho Mountains from the Colorado River northwest into the Imperial Valley. The gravity study gives no indication of buried bedrock highs in the basin between Pilot Knob and the Cargo Muchacho Mountains (figs. 9 and 11) that would impede ground-water flow from the Colorado River and the All-American Canal to the west toward the Salton Sea. Well data and gravity studies indicate a maximum thickness of 1,080 feet of low-density sediments along a profile between Pilot Knob and the Cargo Muchacho Mountains (fig. 9). Depth to bedrock increases to the west in that basin. Depth to bedrock also increases to the north beneath Picacho Mesa. The complete Bouguer anomaly map exhibits regional gradients to the west and to the north and a northwestward-trending trough extending from southeast of Yuma to Picacho Mesa and farther to the northwest. Because of the limited areal extent of interest for this study, the map was left as complete Bouguer, and no regional trend surface was removed. Trends were removed instead along profiles used for two-dimensional models.

The Cargo Muchacho and Chocolate Mountains do not exhibit significant gravity anomalies. In the Chocolate Mountains, the absence of anomaly can be attributed to the sparseness of data, although a line of gravity stations crosses the Chocolate Mountains just west of longitude 114°37′30″. Absence of anomaly in the Cargo Muchacho Mountains exists in spite of many gravity stations on the margins of the range. The small gravity high in sections 2 and 11, T. 21 S., R. 16 E. (SB) is a more pronounced anomaly than anything associated with the Cargo Muchacho Mountains. The absence of anomalies associated with these two ranges might indicate emplacement along low-angle faults.

A two-dimensional gravity model was completed for the profile between Pilot Knob and the Cargo Muchacho Mountains (fig. 9, *B–B’*, fig. 11). An approximately 2.8-milligal-per-mile south to north gradient was removed to give a residual gravity profile. Calibration of density for the alluvium was obtained from depth to bedrock (806 feet) in well N (fig. 9; Loeltz and others, 1975), 0.5 mile west of the middle of the profile. The densities used in the model are 2.07, 2.25, and 2.67 g/cm^3 for unsaturated alluvium, saturated alluvium, and igneous bedrock, respectively. Densities for alluvium correspond to a porosity of 0.25. Simulated greatest depth to bedrock was 1,080 feet below land surface or 770 feet below sea level. The elevation of the water table is about 135 feet across the basin, which yields a value of about 900 feet for maximum saturated thickness of alluvium in the central part of the basin between Pilot Knob and the Cargo Muchacho Mountains.

Simulated depth to bedrock of 240 feet below land surface at test well C did not agree with the actual depth to bedrock of 506 feet. That well may be completed in a buried canyon. The westward-plunging trough that begins east of the middle of gravity profile *B–B’* (fig. 9) and the pass between Ogilby Hills and the Cargo Muchacho Mountains might contain and be indicative of the buried canyon or of a fault zone that exhibits little expression on the gravity map. In the vicinity of test well C, neither the well log nor field evidence indicates the presence of material with a density intermediate between saturated alluvium and bedrock that could resolve the conflict by lowering the simulated bedrock contact.

The density for saturated alluvium of 2.27 g/cm^3 for the simulation at profile *A–A’* and 2.25 g/cm^3 for the simulation along profile *B–B’* were determined independently by adjusting the density until the simulated depth to bedrock matched the depth to bedrock in each of the calibration wells. The agreement among the saturated densities and the depths to bedrock in the two calibration wells indicates that the depth to bedrock at test well C does not represent the general base of the alluvium.

The river aquifer consists of Colorado River sediments and alluvium of local origin that overlie the Bear Canyon fanglomerate of Dillon (1975) and crystalline bedrock units along the southwest flank

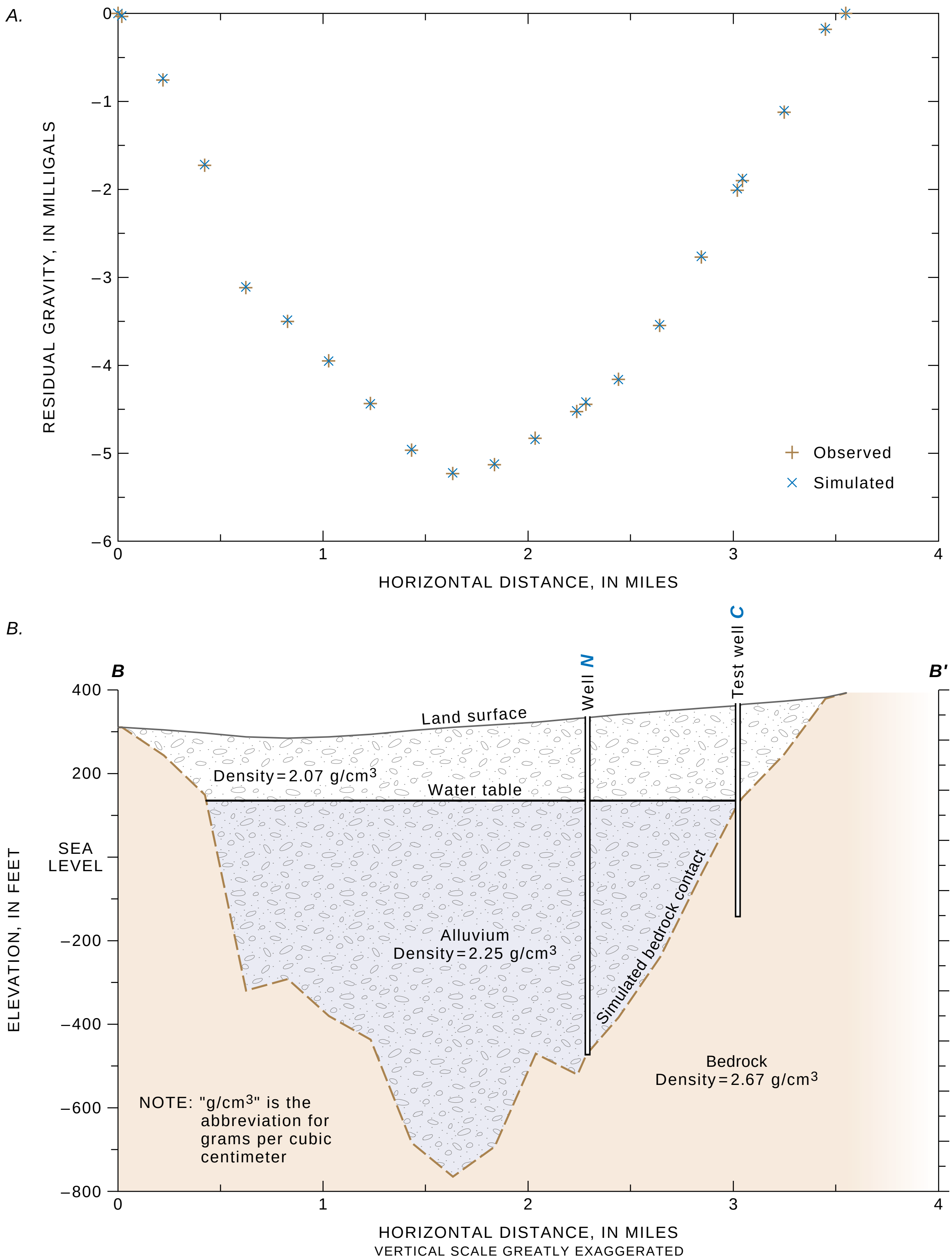


Figure 11. Observed and simulated two-dimensional gravity model for section *B–B'*, Imperial County, California. *A*, Observed and simulated residual gravity. *B*, Gravity model.

of the Chocolate Mountains west and northwest of the Cargo Muchacho Mountains (pl. 3). A test well in Indian Pass and wells in section 33, T. 13 S., R. 19 E. (SB) yield water from the river aquifer. A line of test holes provided data to delineate the edge of the river aquifer in Indian Pass. The river aquifer extends northwestward outside of the study area toward the Salton Sea.

Gila River Canyon

The Gila River entered the Yuma area and cut a canyon between the Laguna and Gila Mountains. Deltaic deposits of the Gila River probably interfinger with those of the Colorado River west of the Gila Gravity Main Canal. Beneath the modern flood plain of the Gila River between the Laguna and Gila Mountains, about 120 to 140 feet of permeable younger alluvium overlies bedrock and forms the river aquifer. The younger alluvium is locally thicker where scour occurred around two bedrock hills in section 4, T. 8 S., R. 21 W. (G & SR; pl. 1). A test well 200 feet north of the south hill penetrated 178 feet of younger alluvium and bottomed on bedrock or a boulder. This probably is the point of minimum cross-sectional area of the aquifer at this locality (fig. 12). The aquifer probably is thin between the north bedrock hill and its edge along the north side of the valley. The main part of the aquifer is about 0.5 to 0.9 mile wide between outcrops of bedrock along each side of the valley and about 0.44 mile wide at the two bedrock hills.

The younger alluvium provides a subsurface connection between the river aquifer in the Yuma area and the aquifer connected to the Gila River upstream from Dome. Depth to water generally is less than 20 feet below land surface on the flood plain and the river aquifer is hydraulically connected to the Gila River. Current (1999) ground-water flow is downvalley from east of Dome into the Yuma area. Insufficient water levels were obtained to produce a map, but the elevation of the water surface in the wells near McPhaul Bridge ranged from 151.76 to 152.92 feet, which is lower than in a well about 3 miles to the east where the elevation of the water surface is 159.66 feet.

Horizontal gravity gradients are low in the vicinity of McPhaul Bridge (fig. 12). Although gravity stations are sparse northwest of McPhaul Bridge, station density is high in the vicinity of the bridge. The two small positive anomalies with maximum contours of -20.2 and -20.4 milligals are associated with the low-permeability igneous outcrops that form the bridge abutments. A gravity low 2 miles to the east indicates a local increased thickness of alluvium. No buried bedrock highs appear to be present to obstruct ground-water flow between the Gila River drainage to the east and the Colorado River drainage to the west. Generally shallow depth to bedrock and apparently limited density contrast between alluvium and underlying bedrock account for the absence of an anomaly to model at McPhaul Bridge. Depth to bedrock ranges from 117 feet at test well S, 127 feet at test well U, to 140 feet at test well T (fig. 12). Depth to bedrock in a local scour hole at test well R, between the igneous abutments, is 178 feet. Of the four known depths to bedrock, only that at test well R is indicated in the gravity data. At test well T, the water table is at an elevation of 153 feet, and the saturated thickness of alluvium is 125 feet.

DELINEATION OF THE RIVER-AQUIFER BOUNDARY

The river-aquifer boundary was delineated primarily on information from previously published geologic, hydrologic, and geophysical studies. Areal extent, saturated thickness below river level, and subsurface continuity of sediments and sedimentary rocks that form the river aquifer were determined by drilling 11 test wells and were inferred from hydrologic, geologic, and geophysical maps and studies and lithologic, geophysical, and drillers' logs of wells. Extent and thickness of low-density sediments that were assumed to form the river aquifer in several areas were determined by gravity studies done during this investigation. The position of the river-aquifer boundary shown on plates 1–3 is intended to be directly above the subsurface intersection of the accounting surface and the bedrock surface (fig. 3). The position is approximate in much of the study area because subsurface data from boreholes or geophysical studies commonly are not available near the edge of the river aquifer. The boundary generally was drawn near or at the surface contact

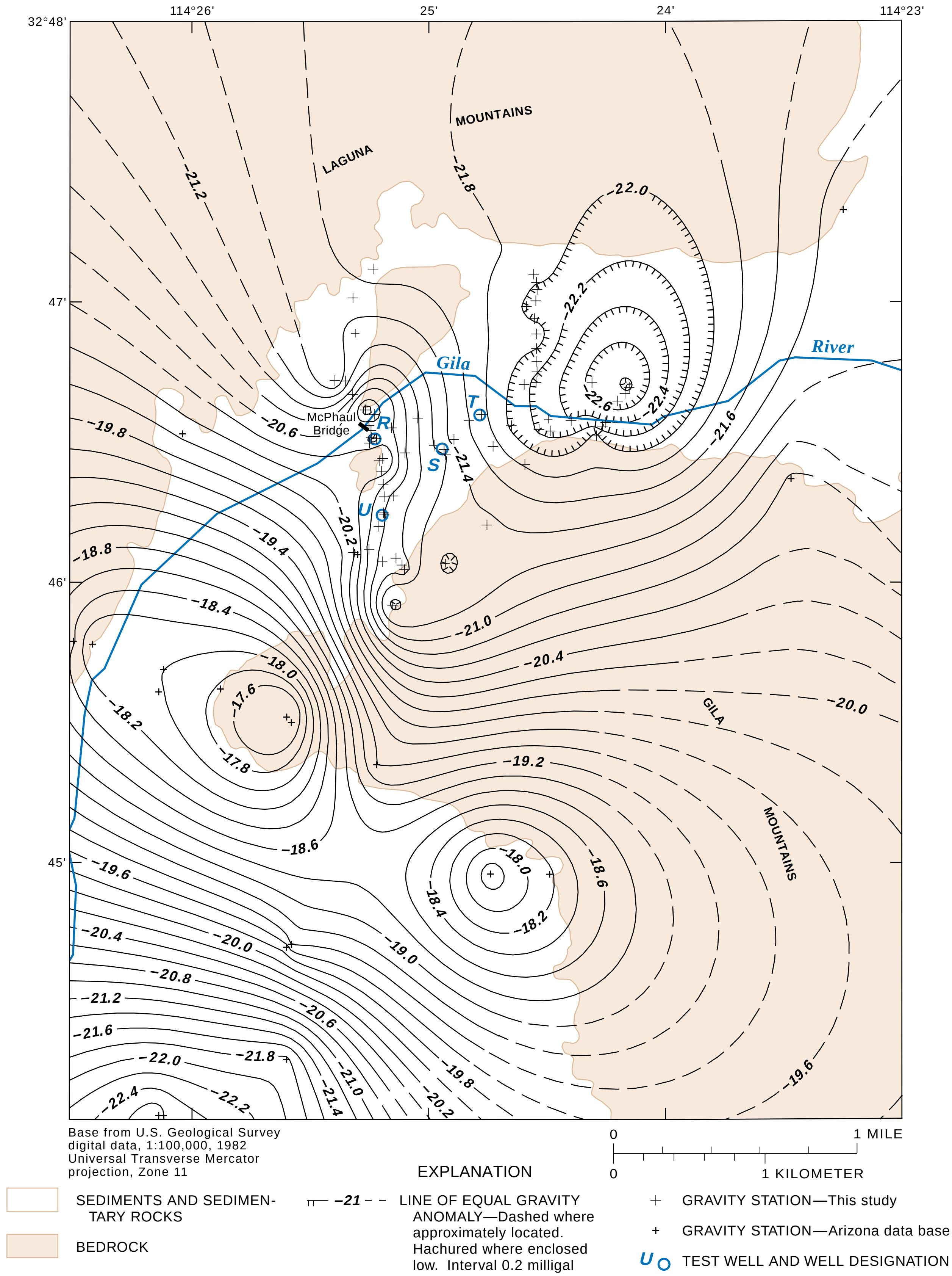


Figure 12. The complete-Bouguer gravity anomaly for lower Gila canyon, Arizona.

between the sediments and sedimentary rocks and the bedrock unless subsurface data were available to better define the position. The river-aquifer boundary was delineated on the basis of the following scientific assumptions (modified from Wilson and Owen-Joyce, 1994):

- The younger alluvium and older alluvium are permeable, hydraulically connected, store and transmit significant quantities of water, and form an aquifer.
- Mountain masses and basin rims of bedrock are effective barriers to ground-water flow; interbasin flow through mountain ranges is negligible in relation to the magnitude of recharge from the Colorado River.
- The position of the river-aquifer boundary generally is a few feet to a few thousands of feet toward the river from the contact between the alluvial slopes and the bedrock because the slopes are underlain by bedrock near the mountains.
- For the purpose of the gravity studies, low-density sediments that fill structural basins between mountains are equivalent to the sediments and sedimentary rocks that form the river aquifer.
- The river aquifer extends from the river beneath the flood plain and alluvial slopes to an intersection with bedrock.
- Saturation and hydraulic connection exist in the river aquifer where several hundred feet of sediments and sedimentary rocks are present below river level between the flood plain and the bedrock.
- Static water-level elevations in wells on the alluvial slopes and in adjacent valleys provide local values of the elevation of the water table and indirect evidence of hydraulic connection to the flood plain where sufficient wells are available to define the water table.

The boundary of the river aquifer is delineated from the northwest end of the study area in Imperial Valley, California, to the international boundary with Mexico in Arizona. Although the river aquifer is continuous beneath the international boundary with Mexico, this study is confined to the United States. The river aquifer is continuous beneath the flood plain of the Colorado River upstream and downstream from Laguna Dam between the bedrock of the Chocolate and Laguna Mountains. The river aquifer boundaries upstream and downstream from Laguna Dam join at Laguna Dam (pl. 1). Delineation of the river-aquifer boundary in several localities of the study is described below.

In Arizona, the boundary of the river aquifer generally is drawn along the southwestern flank of the Laguna, Gila, and Tinajas Altas Mountains near the contact with bedrock (fig. 1; pls. 1–2). The boundary is drawn around the exposed bedrock of the Butler Mountains (pl. 2). The river-aquifer boundary is drawn along the bedrock contact of the Boundary Hills in the United States. The Boundary Hills are the only outcrop of bedrock along the international boundary with Mexico (pl. 2).

In the Gila River canyon between the Laguna and Gila Mountains, the river-aquifer boundary is drawn along the edges of the Gila River flood plain close to the contact between bedrock and younger alluvium or older alluvium. The river-aquifer boundary is drawn around two bedrock hills in the flood plain at the probable point of minimum cross-sectional area of the aquifer where permeable younger alluvium provides a subsurface hydraulic connection between the river aquifer along the Colorado River to a similar aquifer along the Gila River upstream from Dome (site 4, pl. 1). Water levels in this area are more than 30 feet above the accounting surface. The river-aquifer boundary lines were ended near the Dome streamflow-gaging station because that is the extent of the Lower Colorado River Accounting System (Owen-Joyce and Raymond, 1996; Bureau of Reclamation, 1997–99).

In California, the river-aquifer boundary is drawn close to bedrock outcrops along the southwestern flank of the Chocolate Mountains from Laguna Dam to a point northeast of the Cargo Muchacho Mountains. The river-aquifer boundary continues near bedrock outcrops along the east side of the Cargo Muchacho Mountains to the southeast point of the outcrops and is drawn around a bedrock hill south and east of the mountains. The aquifer probably is thin in sections 2 and 3, T. 16 S., R. 21 E. (SB). The boundary is drawn along the south side of the Cargo Muchacho Mountains to the gap between the mountains and the Ogilby Hills.

The river-aquifer boundary continues along the northeast side of the gap between the Cargo Muchacho Mountains and the Ogilby Hills and is drawn separately around the Ogilby Hills on the southwest side of the gap into southeast Imperial Valley (fig. 1; pl. 1). The river-aquifer boundary is drawn along the southwest side of the Cargo Muchacho Mountains to a point in Indian Pass where it continues northwest along the flank of the Chocolate Mountains and ends at 33 degrees north latitude. Although the river aquifer is continuous in the subsurface northwestward toward the Salton Sea, the study area was ended at 33 north latitude and 115 degrees west longitude where the elevation of the water table is below river level.

GENERATION OF THE ACCOUNTING SURFACE

The accounting surface was generated by using water-surface profiles of the perennial Colorado River from Laguna Dam to Morelos Dam. The accounting surface was generated without consideration of the time required for water to travel from the river to any point of withdrawal from the river aquifer. The elevation and slope of the accounting surface are shown on the maps by contours that extend from the edge of the flood plain to the river-aquifer boundary along the mountains (fig. 3; pl. 1). The contours are oriented approximately perpendicular to the inferred general direction of flow of the river and ground water beneath the flood plain and alluvial slopes of the river aquifer (pl. 1). The contours are curved and oriented to indicate interpreted water flow away from or toward the river or flood plain near bends in the river. Some adjustments were made to the spacing of the contours to minimize the effects of the curvature of the river where it is several miles east of the northwest edge of the flood plain (pl. 1). The elevation of the accounting surface is based on the river profile upstream from the northerly international boundary streamflow-gaging station (site 7, pl. 1). In California, the accounting surface is delineated to where the elevation of the water table is about 105 feet (pl. 1). Because of limited well data, use of the 105-foot contour provides a buffer to the approximate limit of river water stored above river level (pl. 1). In Arizona, the accounting surface is delineated to about the downstream limit of perennial flow in the Colorado River at Morelos Dam.

River water-surface profiles were computed on the basis of regulated-flow conditions of the late 1990’s, delivery of full allocations of Colorado River water to users in the United States, delivery of the full treaty obligation to Mexico, and river-channel conditions surveyed by the Bureau of Reclamation in 1998. The profiles were computed for a “normal” flow regime downstream from Laguna Dam. Frequent changes occur in the flow regime along the river because of seasonal cropping patterns, flood-control releases from upstream reservoirs, flooding of tributaries, fluctuations in quantity of agricultural drainage, sluicing operations, and river-channel maintenance. The profile was smoothed at points of change in discharge.

Discharges selected for computation of the river water-surface profiles are based on average cropping patterns and agricultural drainage, neither flood nor drought conditions, and no operational activities. The Bureau of Reclamation computed the profiles with the HEC-RAS program using hydraulic routing and step-backwater methods (Donald Young, Bureau of Reclamation, written commun, 1998; Jeffrey Addiego, Bureau of Reclamation, written commun., 1999). The discharges used to compute the profiles of the various reaches of the Colorado River for 1998–99 are as follows:

Reach	Discharge, in cubic feet per second
Laguna Dam to Gila River	430
Gila River to Yuma Main Canal wasteway	630
Yuma Main Canal wasteway to Pilot Knob wasteway	1,830
Pilot Knob wasteway to Morelos Dam	2,935

POTENTIAL ADJUSTMENTS TO THE METHOD

The accounting surface was generated from water-surface profiles of the lower Colorado River, which were computed on the basis of regulated flow conditions of the late 1990’s, delivery of full allocations of Colorado River water to users in the United States, delivery of the full treaty obligation to Mexico, and river-channel conditions surveyed by the Bureau of Reclamation in 1998. Major changes in any of these conditions could result in changes of the water-surface elevation in the river channel, which could lead to an adjustment of the accounting surface.

Future increases in pumping from existing wells or development of new well fields in areas outside the flood plain could cause static water-level elevations in wells that initially were above the accounting surface to decline to or below the elevation of the accounting surface. The lowering of static water-level elevations below the accounting-surface elevation in wells in these areas would result in a change in the designation of the wells that are presumed to yield water that will be replaced by river water stored above river level to wells that are presumed to yield water that will be replaced by water from the Colorado River. Lining of the All-American Canal, as proposed by California, will eliminate the source of water for the ground-water mound in southeast Imperial Valley. Monitoring changes in the water table used to define the elevation and shape of ground-water mounds could provide estimates of changes in the quantity of water stored above river level.

Periodic monitoring and evaluation of channel conditions, river discharges, and water-level elevations in the mounds would provide information needed to determine if an adjustment to the elevations of the accounting surface is warranted. High flows from the Gila River in 1993 deposited more than 10 million cubic yards of sediment in the Colorado River channel upstream from Morelos Dam and raised the river bed about 5 feet; the Bureau of Reclamation plans to dredge some of this sediment to improve the capacity of the river in the Yuma area (Bureau of Reclamation, 1999). Subsurface conditions in the river aquifer are poorly known near the boundaries of the river aquifer in many areas. Monitoring future geologic and geophysical studies and well drilling will provide new information that could allow refinement of the position of the boundaries of the river aquifer.

SUMMARY

Accounting for the use of Colorado River water is required by the U.S. Supreme Court decree, 1964, *Arizona v. California*. Water pumped from wells on the flood plain and from certain wells on alluvial slopes outside the flood plain is presumed to be river water and is accounted for as Colorado River water. The accounting-surface method developed for the area upstream from Laguna Dam was modified for use downstream from Laguna Dam to identify wells outside the flood plain of the lower Colorado River that are presumed to yield water that will be replaced by water from the river. Use of the same method provides a uniform criterion of identification that is based on hydrologic principles for all users who pump water from wells.

The accounting-surface method is based on the concept of a river aquifer and an accounting surface within the river aquifer. The river aquifer consists of permeable sediments and sedimentary rocks that are hydraulically connected to the Colorado River so that water can move between the river and the aquifer in response to withdrawal of water from the aquifer or differences in water-level elevations between the river and the aquifer. The flood plain and adjacent alluvial slopes in the Yuma area and in southeast Imperial Valley are underlain by the river aquifer. The river aquifer includes the younger alluvium and older alluvium, which overlie nearly impermeable bedrock. The older alluvium includes the Bouse Formation and the conglomerate of the Chocolate Mountains. The subsurface limit of the river aquifer is the nearly impermeable bedrock of the bottom and sides of the basins that underlie the Yuma area and adjacent tributary valleys. The accounting surface represents the elevation and slope of the unconfined static water table in the river aquifer outside the flood plain of the Colorado River that would exist if the river were the only source of water to the river aquifer. The accounting surface was generated by using water-surface profiles of the Colorado River from Laguna Dam to about the downstream limit of perennial flow at Morelos Dam. The accounting surface extends outward from the edge of the flood plain to the subsurface boundary of the river aquifer and was generated on the basis of water-surface profiles of the lower Colorado River computed by the Bureau of Reclamation with the HEC-RAS program using hydraulic routing and step-backwater methods on the basis of regulated flow conditions of the late 1990’s. This method provides a way to identify those wells presumed to yield water that will be replaced by water from the river by determining if the elevation of the static water table at a well is above or below the accounting surface.

Wells that have a static water-level elevation equal to or below the accounting surface are presumed to yield water that will be replaced by water from the river. Pumping water from a well completed in the river aquifer where the elevation of the static water level in the well is below the elevation of the accounting surface will eventually cause movement of water from the river into the river aquifer. Wells that have a static water-level elevation above the accounting surface are presumed to yield river water stored above river level. If more water is pumped from the well than can be replaced from the ground-water mound, water-level elevations in the well will decline below the accounting surface and water will eventually move toward the well from the river.

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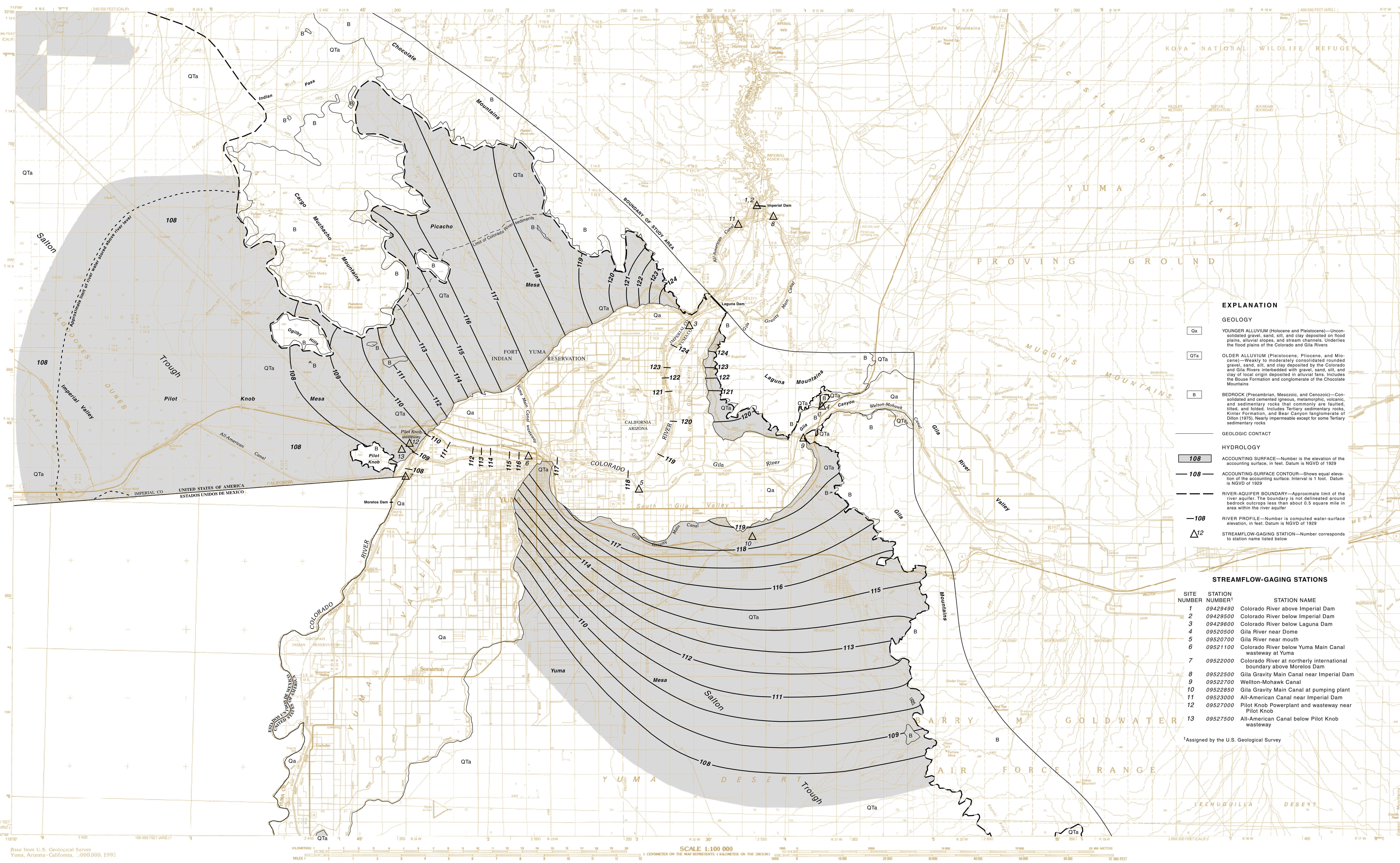


EXPLANATION

GEOLOGY

Qa — YOUNGER ALLUVIUM (Holocene and Pleistocene)—Unconsolidated gravel, sand, silt, and clay deposited on flood plains, alluvial slopes, and stream channels. Underlies the flood plains of the Colorado and Gila Rivers

QTa — OLDER ALLUVIUM (Pleistocene, Pliocene, and Miocene)—Weakly to moderately consolidated rounded gravel, sand, silt, and clay deposited by the Colorado and Gila Rivers interbedded with gravel, sand, silt, and clay of local origin deposited in alluvial fans. Includes the Bouse Formation and conglomerate of the Chocolate Mountains

B — BEDROCK (Precambrian, Mesozoic, and Cenozoic)—Consolidated and cemented igneous, metamorphic, volcanic, and sedimentary rocks that commonly are faulted, tilted, and folded. Includes Tertiary sedimentary rocks, Kinter Formation, and Bear Canyon fanglomerate of Dillon (1975). Nearly impermeable except for some Tertiary sedimentary rocks

GEOLOGIC CONTACT

HYDROLOGY

108 — ACCOUNTING SURFACE—Number is the elevation of the accounting surface, in feet. Datum is NGVD of 1929

—108— ACCOUNTING-SURFACE CONTOUR—Shows equal elevation of the accounting surface. Interval is 1 foot. Datum is NGVD of 1929

RIVER-AQUIFER BOUNDARY—Approximate limit of the river aquifer. The boundary is not delineated around bedrock outcrops less than about 0.5 square mile in area within the river aquifer

—108 RIVER PROFILE—Number is computed water-surface elevation, in feet. Datum is NGVD of 1929

△12 STREAMFLOW-GAGING STATION—Number corresponds to station name listed below

STREAMFLOW-GAGING STATIONS

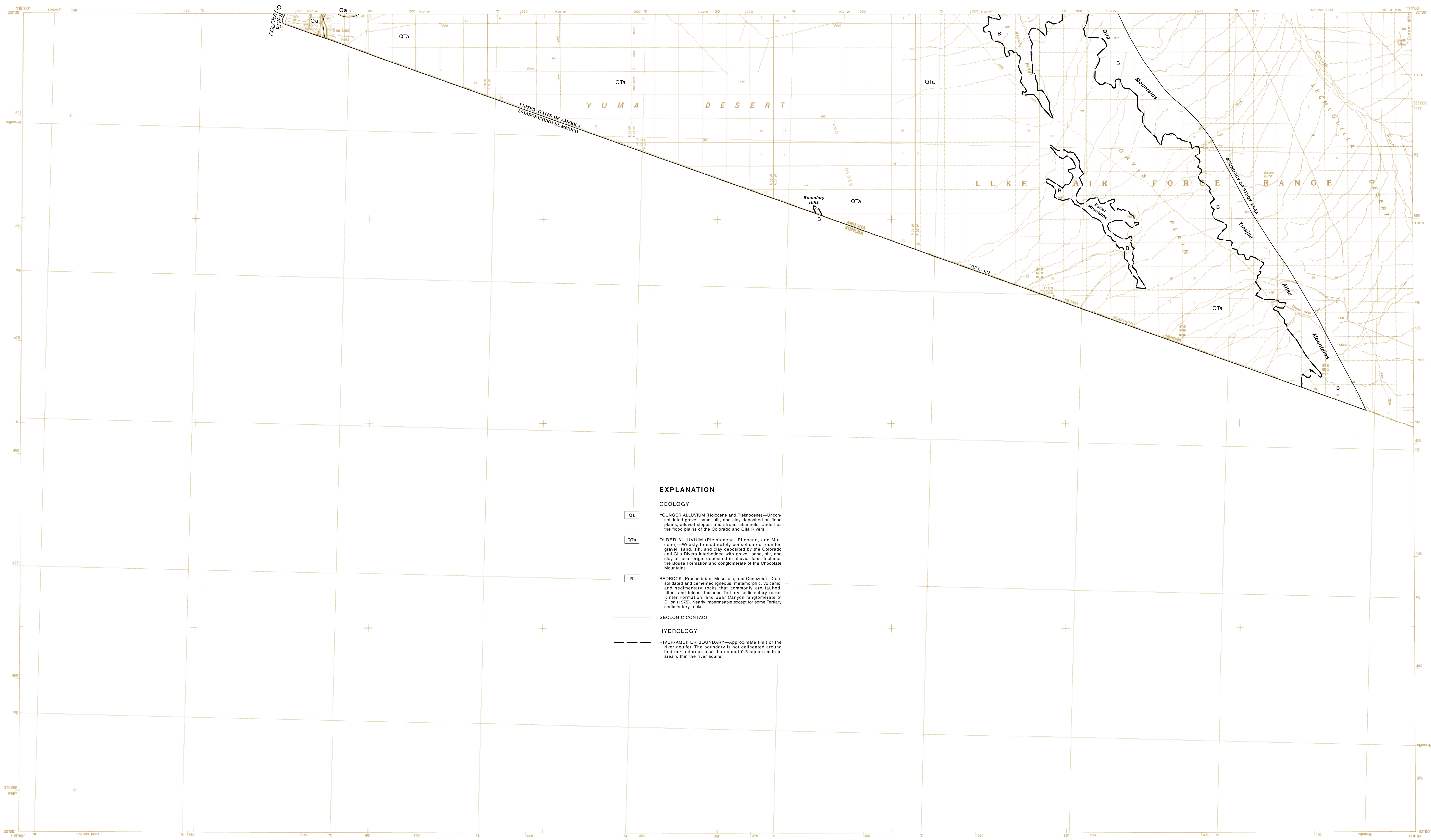
SITE NUMBER	STATION NUMBER[1]	STATION NAME
1	09429490	Colorado River above Imperial Dam
2	09429500	Colorado River below Imperial Dam
3	09429600	Colorado River below Laguna Dam
4	09520500	Gila River near Dome
5	09520700	Gila River near mouth
6	09521100	Colorado River below Yuma Main Canal wasteway at Yuma
7	09522000	Colorado River at northerly international boundary above Morelos Dam
8	09522500	Gila Gravity Main Canal near Imperial Dam
9	09522700	Wellton-Mohawk Canal
10	09522850	Gila Gravity Main Canal at pumping plant
11	09523000	All-American Canal near Imperial Dam
12	09527000	Pilot Knob Powerplant and wasteway near Pilot Knob
13	09527500	All-American Canal below Pilot Knob wasteway

[1]Assigned by the U.S. Geological Survey

RIVER AQUIFER AND ACCOUNTING SURFACE IN THE YUMA AREA AND SOUTHEAST IMPERIAL COUNTY BELOW LAGUNA DAM, YUMA, ARIZONA–CALIFORNIA

By
Richard P. Wilson
2000

Sandra OwenJoyce, Richard P. Wilson, Michael C. Carpenter, and James B. Fink



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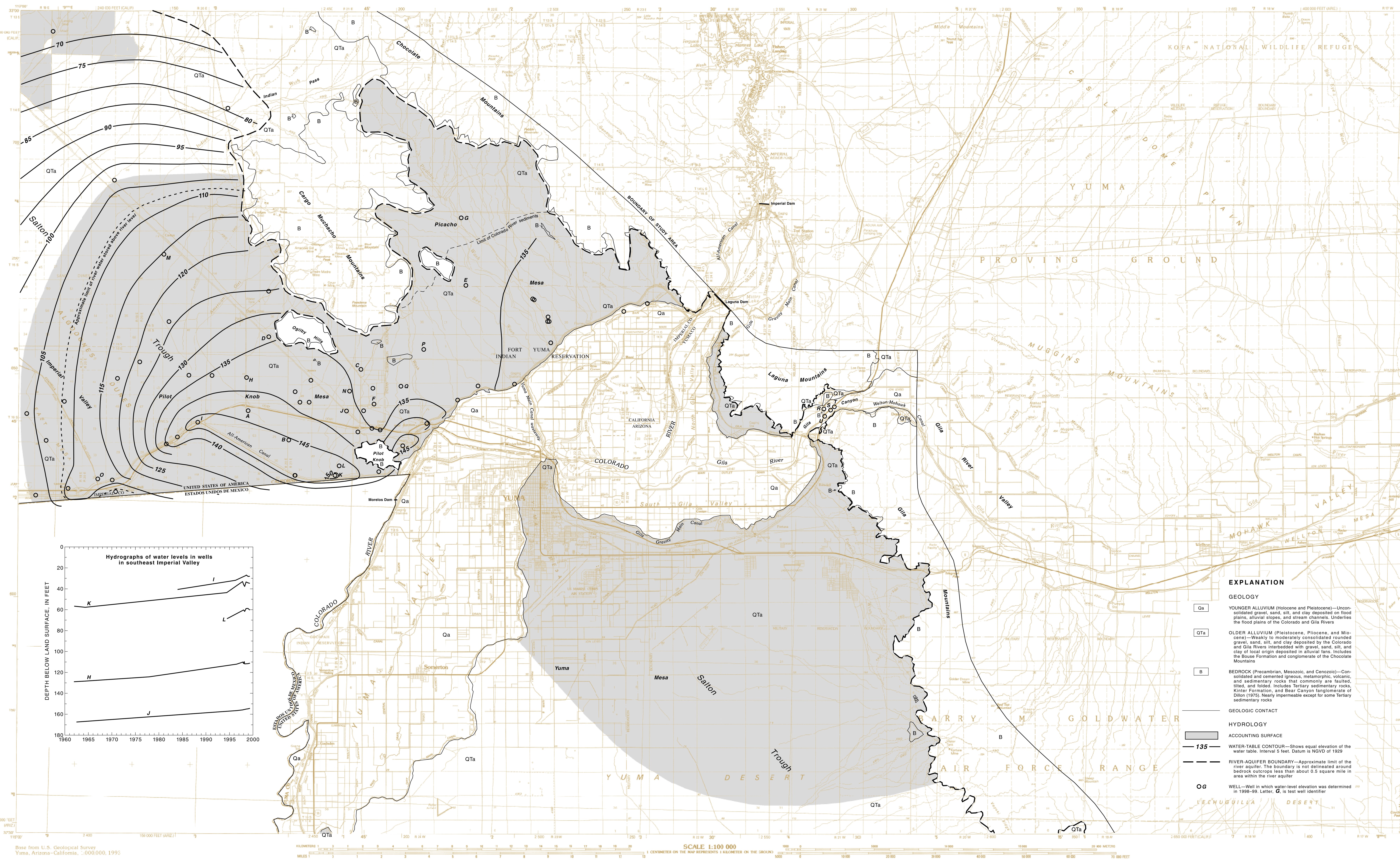
Base from U.S. Geological Survey
Tinajas Altas Mts., Arizona, 1:000,000, 1980

SCALE 1:100 000
1 CENTIMETER ON THE MAP REPRESENTS 1 KILOMETER ON THE GROUND

RIVER AQUIFER IN THE YUMA AREA DOWNSTREAM FROM LAGUNA DAM, TINAJAS ALTAS, ARIZONA

By
Richard P. Wilson
2000

PREPARED IN COOPERATION WITH THE
BUREAU OF RECLAMATION



ELEVATION OF THE WATER TABLE IN SOUTHEAST IMPERIAL COUNTY, CALIFORNIA, 1998–99

By
Richard P. Wilson
2000

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